EFFECTS OF POLYETHYLENE-OXIDE SOLUTIONS ON THE PERFORMANCE OF A SMALL PROPELLER

LEE HERMAN HENDERSON

LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIF. 93940

United States
Naval Postgraduate School

LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIF. 93940

THESIS

EFFECTS OF POLYETHYLENE-OXIDE SOLUTIONS ON THE PERFORMANCE OF A SMALL PROPELLER

by

Lee Herman Henderson

Thesis Advisor: James V. Sanders

September 1971

Approved for public release; distribution unlimited.

Effects of Polyethylene-Oxide Solutions on the Performance of a Small Propeller

by

Lee Herman Henderson
Lieutenant Commander, United States Navy
B.S., Michigan Technological University, 1961

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING ACOUSTICS

from the

NAVAL POSTGRADUATE SCHOOL
September 1971

H4395
c1

ABSTRACT

The thrust and torque were measured and the efficiency calculated for a 14.6-cm diameter, two-bladed propeller in aqueous solutions of polyethylene oxide, WSR-301, with concentrations ranging from 0 to 75 wppm (weight parts per million). The full operating range of the propeller was studied. For the propeller operating under heavily loaded conditions, the thrust decreases with increasing concentration while the torque passed through a minimum at 10 wppm. This resulted in an increase in efficiency (η_p=VT/Qw, where V is the speed of advance, T is the thrust, Q is the torque, and w is the angular frequency of rotation) of up to 10% at 10 wppm. For the propeller operating under lightly loaded conditions, the polymer had little effect on performance. If these results are applicable to full-sized propellers, drag-reducing polymers would not effect propeller performance significantly. Acoustic measurements were also made and they indicate that the polymer has no effect on the strength of the discrete components of the radiated propeller noise.

TABLE OF CONTENTS

I. INTRODUCTION ---------- 8
  A. GENERAL ---------- 8
  B. WATERBORNE VEHICLES ---------- 9
  C. ROTATING DISKS ---------- 11
  D. HYDROFOILS AND PROPELLERS ---------- 12
II. EXPERIMENTAL PROCEDURES ---------- 15
  A. APPARATUS ---------- 15
  B. PROCEDURE ---------- 16
    1. Water Velocity Measurements ---------- 16
    2. Motor Efficiency Calibration ---------- 17
    3. Determination of Propeller Parameters ---------- 19
  C. POLYMER MIXING AND DEGRADATION ---------- 22
III. EXPERIMENTAL RESULTS ---------- 24
  A. GENERAL ---------- 24
  B. THRUST ---------- 25
  C. TORQUE ---------- 25
  D. PROPELLER EFFICIENCY ---------- 26
IV. SUMMARY AND CONCLUSIONS ---------- 28
APPENDIX A. EFFECTS OF POLYMER SOLUTIONS ON THE DISCRETE COMPONENTS OF PROPELLER NOISE ---------- 58
BIBLIOGRAPHY ---------- 62
INITIAL DISTRIBUTION LIST ---------- 66
FORM DD 1473 ---------- 68

LIST OF ILLUSTRATIONS

1. Circular Tank--30
2. Motor and Strain Gauge Mounting ---------------------30
3. Motor Supporting Frame-------------------------------31
4. Motor and Propeller Assembly-------------------------31
5. Flow Restrictor--------------------------------------32
6. Water Velocity Measuring Equipment-------------------32
7. Water Velocity Measurement Switching Circuit---------33
8. Propeller Design-------------------------------------34
9. Motor Efficiency-------------------------------------35
10. Strain Gauge Calibration----------------------------36
11. Torque Degradation----------------------------------37
12. Thrust Degradation----------------------------------38
13. Thrust for J = 0.040--------------------------------39
14. Torque for J = 0.040--------------------------------40
15. Propeller Efficiency for J = 0.040------------------41
16. Propeller Performance for Constant RPM for J = 0.040-42
17. Thrust for J = 0.104 -------------------------------43
18. Torque for J = 0.104 -------------------------------44
19. Propeller Efficiency for J = 0.104------------------45
20. Propeller Performance for Constant RPM for J = 0.104-46
21. Thrust for J = 0.165--------------------------------47
22. Torque for J = 0.165--------------------------------48
23. Propeller Efficiency for J = 0.165------------------49
24. Propeller Performance for Constant RPM for J = 0.165-50
25. Thrust for J = 0.205--------------------------------51

26. Torque for J = 0.205------------------------------------52

27. Propeller Efficiency for J = 0.205-------------------53

28. Propeller Performance for Constant RPM for J = 0.205-54

29. Propeller Performance Comparison for Optimum 10 wppm at 1000 RPM---55

30. Propeller Performance Comparison for Optimum 10 wppm at 1400 RPM---56

31. Propeller Performance Comparison for Optimum 10 wppm at 1800 RPM---57

32. Acoustic Blade Signal for J = 0.040, 0.104-----------60

33. Acoustic Blade Signal for J = 0.165, 0.205-----------61

LIST OF SYMBOLS

C	Concentration dependent parameter
D	Diameter of the propeller
f	Frequency of rotation (CPS)
h	Number of propeller blades
I	Electrical current
J	Advance coefficient
K_m	Torque coefficient for a rotating disk
K_q	Torque coefficient for a propeller
K_t	Thrust coefficient for a propeller
Pa	Pascal (N/m^2)
Q	Torque
R	Radius of a rotating disk
R_e	Reynolds Number
T	Thrust
V	Water velocity (speed of advance)
V^*_{crit}	Shear velocity at the onset of drag reduction
w	Angular frequency of rotation
η_m	Motor efficiency
η_p	Propeller efficiency
ν	Kenetic viscosity of the solvent
ρ	Density
υ	Electrical voltage

ACKNOWLEDGEMENTS

It is with much gratitude that this author acknowledges all who have assisted in this work. The financial support provided by the generous gift of an electric outboard motor from Mr. D. Beardsley of the Shakespeare Company, Kalamazoo, Michigan is gratefully acknowledged. The friendliness and interest of Dr. J.W. Hoyt of the Naval Undersea Research Center is appreciated. The encouragement of Capt. G.L. Page, USN and Cdr. L. Phillips, USN helped in my decision to pursue an education in underwater physics. I am thankful for this and for the friendship they have extended. For all of his guidance and understanding I am very grateful to have had Prof. J.V. Sanders as my thesis advisor. To my wife and family goes my deepest appreciation for the support and love given to their husband and father during his efforts in this thesis and always in his career as a US naval aviator.

I. INTRODUCTION

A. GENERAL

A scientist's interest in a subject is significantly increased when an unexplained phenomenon exists that has potential application. Such is the case for hydrodynamic drag reduction by the use of polymer additives. One possible application that comes immediately to mind is the ejection of such polymers into the flow past a ship to increase its' speed. While this possibility has been extensively investigated in the past few years, one important question has received relatively little attention: What happens to the propeller efficiency?

The reduction of drag by polymer additives was first reported in 1946 by Vanoni [38], with subsequent work by Toms [37], and Mysels [19]. Unfortunately, this work was not appreciated until 1959 when Merrill [15], and Dodge and Metzner [2] demonstrated its importance. Other early papers of importance in the subject are those by Pruitt and Crawford [29], Hoyt and Fabula [7], and Savins [33].

From 1960 to the present, the growing interest in polymer drag reduction is indicated by the increasing number of papers upon the subject in the literature. However, McNally [14] and Kinnier [11] have emphasized that the number of contradictions appearing in these papers is also growing. For example, it was reported that the turbulent structure of the flow is either changed (Shaver [35], Virk [39] or unchanged (Goldstein [3], Wells [41]); the transition from a laminar to a turbulent flow regime is either delayed (Hershey and

Zakin [6], Savins [33], White [42]) or advanced (Ram and Tamir [30], Paterson [28], Goldstein [4]); etc. This paper will introduce still another contradiction. Kowalski [13] reported that the torque coefficient for a propeller is increased by polymer addition, while results presented in this paper will show a decreased torque coefficient.

Since the actual mechanism responsible for the drag reduction is not fully understood, it should be kept in mind that different types of flow situations may behave differently for the same solution. In particular it should be noted that all works performed upon propellers, including the work reported in this paper, employed a single propeller type. Whether the effect of drag-reducing polymers is critically dependent on propeller design is a question left to future experiments.

B. WATERBORNE VEHICLES

Besides the obvious potential application of polymer additives for large commercial ships, possible naval applications are also evident. A few extra knots of speed could mean survival in many cases. This interest is evident in reports from US Navy facilities by Fabula [20], Goltfredson [21], Hoyt and associates [23,25], Swanson [26], Green [22], and Arranaza [24].

Initial investigations of the flow of polymer solutions around hull shapes began with the study of the effect of polymers on the fluid flow around flat plates. Early researchers in this area, (Hoyt and Fabula [7], Granville [5], Metzner [16], and Vogel and Patterson [40], agree that a very significant reduction of skin friction is possible. They also found that flow behavior was

similar to that observed in pipe flow experiments. That is, the drag reduction increases rapidly with concentration for very dilute solutions, and then levels off and decreases with further increase in concentration. Moreover, it was discovered that maximum drag reduction can occur at concentrations as low as 10 wppm (weight parts per million). Thus, if polymer solutions were to be used to effect the drag reduction of ships, very dilute solutions would be sufficient.

Early flat plate drag reduction experiments ultimately led to ship model tests. Among the first of these was that by Kowalski [12], who estimated that a significant reduction in the drag upon a 450-foot ship travelling at 18 knots would require the injection of 1300 pounds of polymer per hour. He redundantly pointed out the non-practicability of such an operation. From model tests performed by Gollan, Tulin, and Rudy [9] it was estimated that the frictional drag of a large ship could be reduced by 55% resulting in a 12% reduction of the total drag. This would mean that a ship traveling at 20 knots could increase its' speed to 24 knots, with no additional power requirement, by the injection of polymer.

Realizing that skin friction is only a part of the total drag of a ship, a complete consideration of drag reduction by polymer injection will require an additional investigation of the effects of polymers upon wave drag and separation. However, a significant reduction in skin friction appears possible, and it is generally thought a polymer drag reduction system for waterborne vehicles will be available in the near future.

C. ROTATING DISKS

It seems appropriate to consider previous works on rotating disks in fluids before discussing propellers. In the case of the rotating disk, the main cause of the resistance is the frictional forces between the disk and the fluid. The principal causes of the drag on a propeller are described by Saunders [31]. He states: "(a) The blades encounter friction in passing through the water. (b) The flow around each blade interferes to some extent with flow around the adjacent blades, to the detriment of the action of the whole system." In any case the common factor in drag considerations is the surface friction drag for both the rotating disk and the propeller.

Hoyt and Fabula [7] first reported a reduction of torque in additive solutions. Miloh [17], reported that the torque coefficient for a rotating disk decreases rapidly with increasing polyethylene-oxide concentration until an optimum around 100 wppm is reached. For solutions with concentrations greater than this little further decrease in drag was noted. These results are reminescent of those obtained in the flat plate experiments noted above.

A paper by Bilgen [1] contains a comprehensive examination of the effects of guar gum, polyacrylamide, and polyethylene oxide solutions on the motion of both rough and smooth rotating disks. Significant drag reduction was measured for both rough and smooth disks. Miloh and Poreh [18] reported further measurements of the torque of smooth and rough disks, both free and enclosed and developed a useful theoretical equation for the torque coefficients (K_m) of the free rotating disk in polyethylene-oxide solutions:

$$K_m^{-\frac{1}{2}} = 1.97(1+2C)\log_{10}\left[R_e(K_m)^{\frac{1}{2}}\right] + 1.97C\log_{10}\left[0.21\nu^2/(V_{crit}^{*2}R^2)\right] + 0.03$$

where R_e is the radius of the disk, ν is the kinematic viscosity of the solvent, V_{crit}^{*} is the shear velocity at the onset of drag reduction and C is a concentration dependent parameter. For C = 0 this equation reduces to Goldstein's equation for the free rotating disk in water (Goldstein [4], Schlichting [34]);

$$K_m^{-\frac{1}{2}} = 1.97\log_{10}\left[R_e(K_m)^{\frac{1}{2}}\right] + 0.03.$$

Although not pertinent to this report, past works reveal conflicting statements on the dynamics of rough disks in polymer solutions for both free and enclosed disks. Thus, theory indicates that polymer additives should not have any effect, yet experimental evidence shows a definite drag reduction.

D. HYDROFOILS AND PROPELLERS

Another area where reported information is sparse concerns the effects of polymer solutions on a hydrofoil. Since a propeller is a rotating hydrofoil, a study of the plain hydrofoil would be of great value at the conclusions of this report. The only work reported was that by Sarpkaya and Rainey [36], which is just a small addedum to the principal work done on circular cylinders. Whereas, no comments were made in the abstract or conclusions of this work, plots of lift and drag versus tunnel stagnation pressure for various values of angle of attack in concentrations 0, 25, and 100 wppm polyethylene oxide are presented. Examination of these plots reveal the following points:

1. For angles of attack of zero and three degrees little

change in lift or drag is noted for those solutions tested.

2. For an angle of attack of six degrees no change in lift was noted. No change in drag was noted for 25 wppm, but there is a definite increase in drag for 100 wppm.

3. For an angle of attack of nine degrees the lift was the same for water and 100 wppm, but for 25 wppm the lift was definitely decreased. Little information can be obtained from the drag plot.

4. For an angle of attack of twelve degrees no change in lift is observed, and a slight increase in drag for the 100 wppm concentration is noted.

In summary, no change in lift is noted except for a decrease at an angle of attack of nine degrees and a concentration of 25 wppm. Little change in drag is noted except for high concentration with high angles of attack, where a slight increase in drag is reported. Obviously, further work on hydrofoils in polymer solutions is desperately needed.

The first experiments conducted on propellers in polymer solutions were those by Wu [43]. He used a circulating water channel driven by a propeller with polyethylene oxide as the drag reducing agent. The velocity of the fluid was measured by photographing the motion of a small, neutrally buoyant particle. Concentrations from zero to 500 wppm were examined and it was found that at 500 wppm the water velocity decreased to half that obtained with pure water. Since the actual velocity values are not given in the paper, it is not known whether the flow in the channel was laminar or turbulent. This paper first pointed out the possibility of a reduction of impeller thrust in additive solutions.

Kowalski [13] carried this work a bit farther by actually measuring the torque. His propeller was mounted in a single-pass flow channel on the end of a long drive shaft. A constant speed of advance of four feet per second was used. Polymer was injected into the flow in front of the propeller. From the measured torque and thrust, torque and thrust coefficients were calculated and the efficiency at constant advance coefficient was determined. With polymer addition, it was found that a decreased thrust and an increased torque resulted in a decreased efficiency. In his conclusion Kowalski said: "Results obtained from these preliminary tests indicate a deleterious effect of polymer additives on the performance of a model propeller. The measurements show a reduction of the thrust and an increase of the torque developed by a propeller when the additive is present compared to the values obtained under exactly similar conditions in water alone. The changes of the thrust and torque resulted in a reduction of the propeller efficiency of approximately 5% for 20 wppm average concentrations of polymer."

The increase in torque that Kowalski reported is in direct conflict with the results to be presented in this paper. There are two differences between these experiments. 1) Kowalski ejected the polymer into the flow in front of the propeller whereas in the present report the propeller rotated in a homogeneous mixture. 2) The two propellers are of different design.

In any case it is hoped that more work will be conducted in this area to resolve the discrepancies pointed out here.

II. EXPERIMENTAL PROCEDURE

A. APPARATUS

This experiment was conducted in a small, circular, toroidal shaped tank (Figure 1). The tank has a seven-foot outer diameter, a four-foot inner diameter, and a wall height of eighteen inches. The tank is made of one-quarter inch welded steel plating. A window (26" x 18") consisting of an inner and an outer plexiglass layer is mounted in the side of the tank (Figures 2,4). The outer layer (one-inch thick) is mounted in a water tight aluminum frame, bolted to the tank. The inner layer (one-eighth inch thick) is mounted in a removable aluminum frame and is curved to fit the inside shape of the tank. Free flooding between the plexiglass layers allows non-distorted vision into the tank.

A Shakespeare Model #683549 electric trolling motor and propeller assembly is mounted in the center of the channel, 23 cm from each wall and 20 cm above the bottom of the tank, just inside the window (Figure 4). A three-quarter inch plywood board (cut to fit inside the tank)covers half the water surface, and is placed 40 cm from the bottom of the tank. This is to prevent air bubbles from being drawn down into the field of the propeller during testing. The motor is mounted on a 250-pound rigid steel frame straddling the tank (Figure 3). A 2.2-cm diameter stainless steel cylindrical shaft (Shakespeare Model #691T33-1 motor tube) mounted vertically to the frame, and extending through a 3.2-cm hole in the plywood cover, serves as the supporting arm for the motor and propeller assembly. The motor is located at the end of the shaft 46.0 cm

below the cross arm on the frame. Electrical power to drive the motor was supplied by a variable-voltage power supply (Electro-Mechanical Product Model #S.O.CS918) with a maximum current capacity of 30 amps. By varying the voltage the RPM of the motor could be controlled.

With the propeller rotating, the fluid was allowed to flow around the tank. However, if this fluid flow was left uncontrolled, only a very short range of advance coefficients could be investigated. For this reason a flow restrictor was placed one-third of the way around the tank upstream from the motor (Figure 5). This restrictor is composed of a matrix of ten 3.9-cm diameter vertical cylinders which can be placed in a planar array in the flow. Different advance coefficients were obtained by varying the order and number of cylinders in the restrictor.

B. PROCEDURE

1. Water Velocity Measurements

Every research engineer will testify that when undertaking the task of developing a given experiment the side problems encountered sometimes create a greater challenge than the experiment itself. Such is the case with measuring the water velocity entering the field of the propeller. Normal measuring devices such as pitot tubes and windmilling propellers were not utilized due to the undetermined effects of polymer solutions on such systems. A procedure of measuring ram pressure such as that used by Sarpkaya and Rainey [36] was attempted, but with the low water velocities used in most of this work the inaccuracies were too great to be tolerated.

The procedure finally adopted consisted of the direct timing of the motion of a neutrally buoyant body over a fixed distance.

A thin nylon cord was suspended above the center of the circular tank. Attached to this cord was a horizontal rod which was free to rotate in a horizontal plane. At the short end of this rod was attached a four pound weight for balance. On the long end a fishing bobber with a weight was attached and allowed to rest in equilibrium in the center of the water channel, 20 cm from the bottom. A copper electrode, attached to the bobber, extended above the water surface as an antenna. Two aluminum rods, electrically insulated from the water, were attached to the outer wall of the tank one meter apart and extending over the fluid (Figure 6). An electric potential of thirty-six volts, supplied by two (Power/ Mate Model #BP118) regulated power supplies, was created between the rods and the water within a switching mechanism (Figure 7). As the bobber antenna, freely moving with the fluid, contacted the first rod it activated a counter (Hewlett Packard Model #521A) which counted a one-hundred Hertz signal from a sinusoidal oscillater (CENCO Model #80593). When the bobber antenna contacted the second rod the counter was turned off. The fluid velocity was calculated from the formula:

$$V = 10^4/\text{count} \quad \text{cm/sec.}$$

Ten such counts were made for each velocity measurement and an average taken. A precision of 6% was estimated.

2. Motor Efficiency Calibrations

The propeller torque can be determined from the input electrical power and the angular frequency (w) if the motor efficiency

(η_m) is known. The torque (Q) is given by

$$Q = I\upsilon\eta_m/w \times 10^7 \text{ dyne cm.}$$

where the current (I) is given in amps and the voltage (υ) in volts. With the voltage, current, and propeller RPM being measured directly the only remaining unknown quantity is the motor efficiency.

If it is assumed that the efficiency is only a function of w, the efficiency can be found by measuring the input power for known torques. The propeller was removed and a free smooth disk attached. Measurements of I, υ, and w were performed in pure water. The torque was calculated from Goldstein's equation for Reynolds numbers greater than critical:

$$(K_m)^{-\frac{1}{2}} = 1.97 \log_{10} \left[R_e(K_m)^{\frac{1}{2}}\right] + 0.03,$$

where

$$R_e = R^2 w/\nu.$$

The torque was then calculated from the definition of the torque coefficient for the free rotating disk (Schlichting [34].

$$K_m = 4Q/(\rho w^2 R^5)$$

resulting in

$$Q = K_m \rho w^2 R^5/4.$$

Knowing the power output of the motor to be equal to Qw, and the power input to be equal to Iυ, the motor efficiency is given by

$$\eta_m = Qw/(I\upsilon).$$

An efficiency calibration for the motor was performed in this manner using a disk of 15.3-cm diameter. The motor efficiency is shown in Figure 9.

It should be noted this calibration is based upon three assumptions:

1, Goldstein's transcendental equation applies for the Reynolds numbers used.

2. The motor forebody has no effect on the flow about the disk.

3, The motor efficiency is a function of angular frequency only.

This calibration was used in all torque calculations reported in this paper.

3. Determination of Propeller Parameters

The propeller used in this report is a Shakespeare Model #658P04, nylon, two-bladed outboard trolling propeller. It is 14.62 cm in diameter and has a pitch varying from forty-degrees near the hub to nearly zero at the tip. It is designed with a curved leading edge so as to shed any fouling material that may get caught in the propeller as it rotates (Figure 8). This propeller is mounted just behind the motor and supporting shaft.

The motor is 6.5 cm in diameter and it is assumed in this report that the forebody has negligible effect on the fluid flow. In otherwords, this propeller for all practical purposes is operating as a free propeller.

In propeller theory the advance coefficient has been adopted as a nondimensional load parameter. It is directly proportional to the speed of advance and inversely proportional to RPM. For example: for a heavy load which moves at low speed even though the propeller rotates at high RPM, a low advance coefficient is observed. However, for a light load which is moved at high speed

by a low RPM, a high advance coefficient is observed. It is defined as the ratio of the speed of advance of the propeller through the fluid to the tip speed of the propeller. Thus, the absolute advance coefficient is:

$$V/(\pi f D)$$

where V is the speed of the propeller relative to the distant water, f the rotation frequency, and D the diameter of the propeller. For practical purposes the π is usually dropped, so that the advance coefficient in this report is given as:

$$J = V/(fD).$$

Before this project was begun, it was suspected that for a given flow restriction, the addition of polymer in solution would not change the resistance to flow around the tank. This expectation was based upon the knowledge that the polymer does not affect flow for channel Reynolds numbers below critical. This was confirmed when velocity measurements were made. The values for the advance coefficients for a constant flow restriction turned out to be equal, within five percent for all concentrations. This was true for all RPM values used (a slight decrease in velocity with increasing polymer concentrations was noted, but an error of five percent is within that expected with a six percent error in the water velocity measuring procedure). For these reasons all data for one load-restriction setting correspond to one value of advance coefficient.

For a free propeller it is customary to express the performance in terms of the thrust coefficient (K_t) and torque coefficient (K_q). These coefficients are (Saunders [31]);

$$K_t = T/\rho f^2 D^4$$

and

$$K_q = Q/\rho f^2 D^5 ,$$

where T is the thrust, Q the torque, ρ the density of the fluid, and D the propeller diameter. All data represented herein is represented in terms of these coefficients.

Three values are needed to compute these coefficients. These are thrust (T), torque (Q) and frequency (f). The easiest to obtain is the frequency. The frequency of a strob light (General Radio Co., Model #1531-A) was set at the desired value and the motor speed adjusted until the propeller appeared stationary. For all runs the motor frequency was changed in fifty Hertz steps from eight-hundred to two-thousand Hertz.

Torque was measured by recording the input current on an ammeter (Westinghouse Model #701384) and voltage on a VTVM (Hewlett Packard Model #801), utilizing the formula discussed in part II. B.2 above.

Thrust was found by measuring the bending of the stainless steel shaft while the motor was in operation. A strain gauge (Statham Model #UC3) located 7.3 cm below the shaft frame mount was employed to measure this bending. The output of the strain gauge was read on a Stratham Model #UR5 analog readout meter. Calibration was obtained by recording the strain-gauge reading for known thrust applied by means of a string pulley system. This calibration (Figure 10) closely approximates a straight line with a slope equal to 67, 415 dynes/div. This constant times the strain gauge reading gave a direct measurement of thrust in dynes.

Since the power into the propeller is equal to $(2\pi Qf)$, and the useful power out is equal to (TV), the propeller efficiency (η_p) is given as follows:

$$\eta_p = TV/(2\pi Qf)$$

where

$$T = K_t \rho f^2 D^4$$

and

$$Q = K_q \rho f^2 D^5 .$$

Substituting and cancelling, yields

$$\eta_p = VK_t/(2\pi DfK_q)$$

or

$$\eta_p = JK_t/(2\pi K_q).$$

This is the equation from which the propeller efficiency was calculated in this report.

C. POLYMER MIXING AND DEGRADATION

In this work only polyethylene oxide (more commonly called POLYOX or PEU) WSR 301 was used as an additive, and mixtures are designated in terms of parts per million by weight (wppm). Mixing was accomplished by first mixing the POLYOX resin with Dow Chemical POLYGLYCOL P400. The POLYOX, completely insoluble in POLYGLYCOL, is held in suspension so that when injected into the water it is readily dissolved. The POLYGLYCOL dissolves in the water and has been shown [11] to have no effect on the flow.

After the slurry of POLYOX and POLYGLYCOL was mixed, the tank was filled with water to a depth so that the propeller was completely immersed. The motor was then turned on and set at a propeller RPM of about 1000. Over the uncovered portion of the

tank the slurry was slowly poured into the rotating water. When all the slurry was poured into the tank the mixture was circulated for one hour. After this period water was added to the mixture to a depth of 42 cm which came to the top of the plywood cover.

The data-taking procedure was designed so that all measurements, for a given advance coefficient were obtained from a single "master" solution. This was accomplished by first mixing a "master" solution of 75 wppm. Then the flow restrictor was set and measurements were taken at the assigned RPM. Then a 50 wppm concentration was obtained by draining one-third of the fluid from the tank and refilling with water. After all these data were taken, one-half of this solution was drained and the tank refilled with water to obtain 25 wppm solution. The 10 wppm solution was obtained by draining three-fifths of this solution and refilling. This was all accomplished within a period of five hours. The measurements in pure water were taken before the POLYOX was added.

To check the degradation of the solution a special run was made. A solution of 75 wppm was mixed and checked for changes in the torque and thrust coefficient at 1100 RPM over a five hour period, with the flow restrictor set for an advance coefficient of about 0.09. Readings were taken every half-hour and a plot of thrust and torque coefficients versus time was drawn (Figures 11,12). There was no noticeable change in thrust and an approximately 25% increase in torque.

III. EXPERIMENTAL RESULTS

A. GENERAL

Torque and thrust data were recorded for various values of RPM and the nondimensional coefficients were computed on the Hewlett-Packard calculator, model #9100A. It was necessary to operate the motor for at least one hour before motor efficiency would stabilize. Likewise, consistent readings of torque were possible only after this procedure was followed.

The errors assumed for thrust were a reading error and a slight drift of the strain gauge meter; whereas the torque error is ascribed to a reading error plus a slight drift in motor efficiency. Errors in the motor efficiency calibration are shown in the results as a constant error for all readings and are not included in the torque accuracy. A total accuracy of two percent is assumed reasonable for torque, thrust, and propeller efficiency readings in this paper.

The results are shown in Figures 13-28 where the thrust and torque coefficients, and propeller efficiency are plotted versus RPM for four different values of advance coefficients. The values of advance coefficients were chosen to give a representative picture of the major operating conditions expected of the propeller. Higher values of advance coefficients were not investigated due to the experimental limitation that the only mechanism for driving the water around the tank was that of the experimental propeller itself. Therefore, the highest advance coefficient possible is that with no artificial restriction to flow (Figure 25-28).

After the data were plotted for various values of concentration, sections were taken at RPM values of 1,000, 1,400, and 1,800. The results of these sections are plotted in Figures 16, 20, 24 and 28.

B. THRUST

In almost all cases, at constant RPM, thrust decreased with increasing polymer concentration. This was true except for $J = .205$ (Figure 28). Here it is observed that the polymer has little effect on thrust until a concentration of 50 wppm was reached. For more concentrated solutions than this the thrust decreases. The lessening of thrust for this propeller was most marked at medium and lower values of advance coefficient. However, when the advance coefficient was such that the propeller was near maximum efficiency, dilute solutions (less than 25 wppm) have little effect on thrust (Figure 28).

C. TORQUE

Without a doubt the most interesting part of the results found in this experiment is the effect of polymer solutions on torque. The sections for the lower advance coefficients shown in Figures 16 and 20 indicate a rapid decrease in torque for very dilute concentrations. After 10 wppm, the torque increased to values sometimes higher than those obtained for pure water. Therefore, concentrations greater than 10 wppm are not recommended for two reasons. First, it costs more to attain higher concentrations and second, an unwanted increase in torque is achieved.

To a lesser degree this effect was also noticed at higher values of advance coefficient as shown in Figures 24 and 28. For dilute

solutions a slight decrease to 10 wppm and then a leveling off of torque was evident. This also indicated a favorable concentration of 10 wppm.

It should be noted that very little evidence indicates torque rising above pure water values. This happened only in one case and was for the lowest advance coefficient measured and for the lowest RPM section (Figure 16).

D. EFFICIENCY

The propeller efficiency was solely dependent on the ratio of the coefficients thrust to torque for constant advance coefficients. Efficiency increased for increasing thrust or decreasing torque. The results of this experiment indicate a decrease in both thrust and torque for almost all advance coefficients investigated. If the ratio remained the same there would have been no change in efficiency, but this was not so. From the section plots it is seen that for the lower advanced coefficients investigated the efficiency for concentrations to 10 wppm either increased or remained essentially unchanged depending on RPM (Figures 16 and 20). The higher advance coefficient plots show various changes in efficiency depending on RPM.

The results of propeller efficiency can be summarized from a detailed analysis of Figures 29-31. These show plots of thrust and torque coefficient and propeller efficiency at constant RPM versus advance coefficients for concentrations of zero and 10 wppm. The effect of adding 10 wppm over pure water can be summarized as follows:

1. For low values of advance coefficients, propeller efficiency is increased or remains unchanged depending on RPM. In no case was propeller efficiency decreased.

2. The advance coefficient at which maximum efficiency is obtained is increased.

3. For advance coefficients above that of the pure water maximum efficiency value, the propeller efficiency is increased. This is indicated for all values of RPM observed.

4. For advance coefficients slightly less than the pure water maximum-efficiency value, the propeller efficiency is either decreased or unchanged depending on RPM.

Concentration greater than 10 wppm indicates a general decrease in propeller efficiency. For this reason only the optimum value of 10 wppm is plotted for analysis in Figures 29-31.

IV. CONCLUSIONS AND SUMMARY

This experiment was conducted with the objective of determining the effects of polyethylene-oxide solutions on the performance of a model propeller. Investigations included:

1. Concentrations of 0, 10, 25, 50, and 75 wppm.
2. Speed of rotations ranging from 850 to 2,000 RPM.
3. Advance coefficients ranging from zero to the pure-water maximum efficiency value which was J = 0.2.

Values of the thrust coefficients were calculated from the readings of a strain gauge mounted on the motor-supporting shaft. Torque coefficients were computed from the motor input electrical power and the motor efficiency curve. From these the propeller efficiency was computed over the designed operating range of the propeller.

The following is a summary of observations and conclusions based on the results of this experiment.

1. The thrust of a propeller is reduced in polymer solutions when compared to that in pure water.
2. The thrust is reduced proportionally to the increasing concentration used.
3. At constant RPM, torque is less for 10 wppm than for pure water. However, a second maximum is sometimes present for concentrations between 25 and 50 wppm. This gives an optimum concentration of 10 wppm.
4. The optimum concentration for minimum torque results in an observed maximum efficiency over most of the advance coefficient range for 10 wppm.

5. When the propeller is operated under a heavy load (low advance coefficient) the addition of 10 wppm to pure water will give an increased propeller efficiency of up to 10%.

6. When operating under very light load conditions (high advance coefficient) the addition of 10 wppm to pure water could have a deleterious effect on the propeller efficiency. This could be as much as a 10% decrease.

7. The addition of 10 wppm will increase the value of advance coefficient for maximum propeller efficiency.

If the results of this experiment are applicable to large propellers, then it can be assumed that if polyethylene oxide is to be used for the reduction of drag on a large waterborne vehicle (such as a ship) there would be no decrease in the propeller performance. This situation represents a heavily loaded propeller, and there could be as much as a 10% increase in efficiency in addition to the benefits of the drag reduction on the hull, if no more than 10 wppm is present in the field of the propeller. Higher concentrations may give a slightly decreased efficiency. If the propeller is mounted on a fast moving vehicle, such as a planing speed boat, a decrease in propeller efficiency is expected as indicated by Kowalski [13]. In this case the question is one of whether the hull drag reduction will over-ride this propeller deficiency. This is a question for each specific case and cannot be resolved in general here.

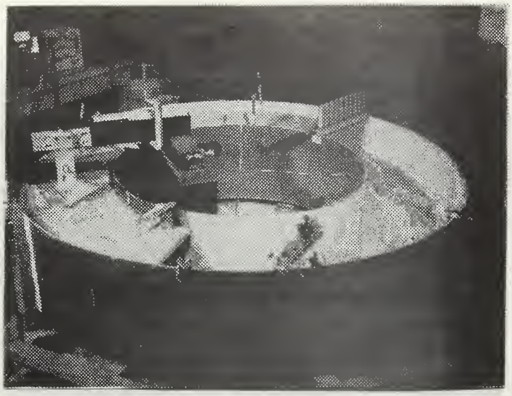


Figure 1. Circular Tank

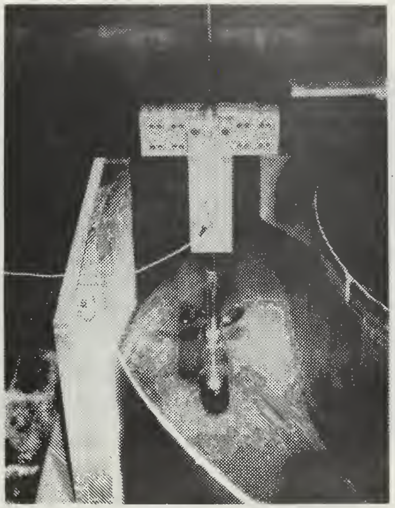


Figure 2. Motor and Strain Gauge Mounting

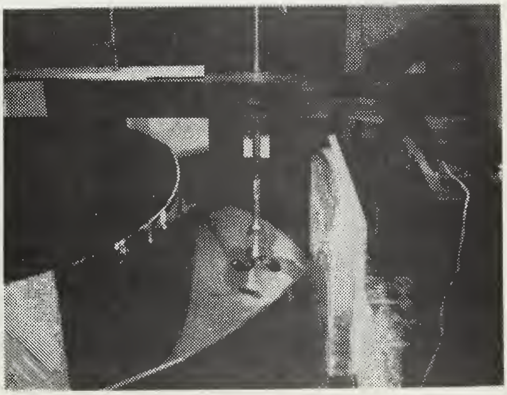


Figure 3. Motor Supporting Frame

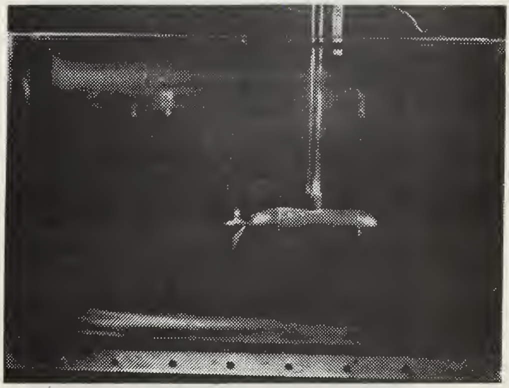


Figure 4. Motor and Propeller Assembly

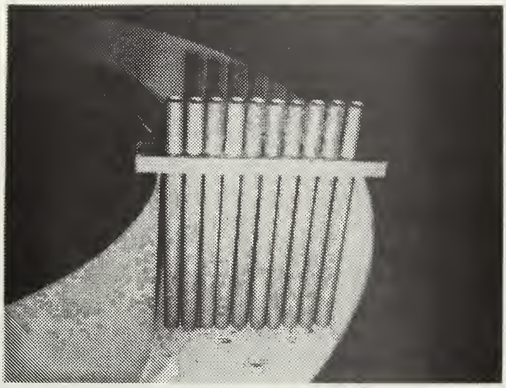


Figure 5. Flow Restrictor

Figure 6. Water Velocity Measuring Equipment

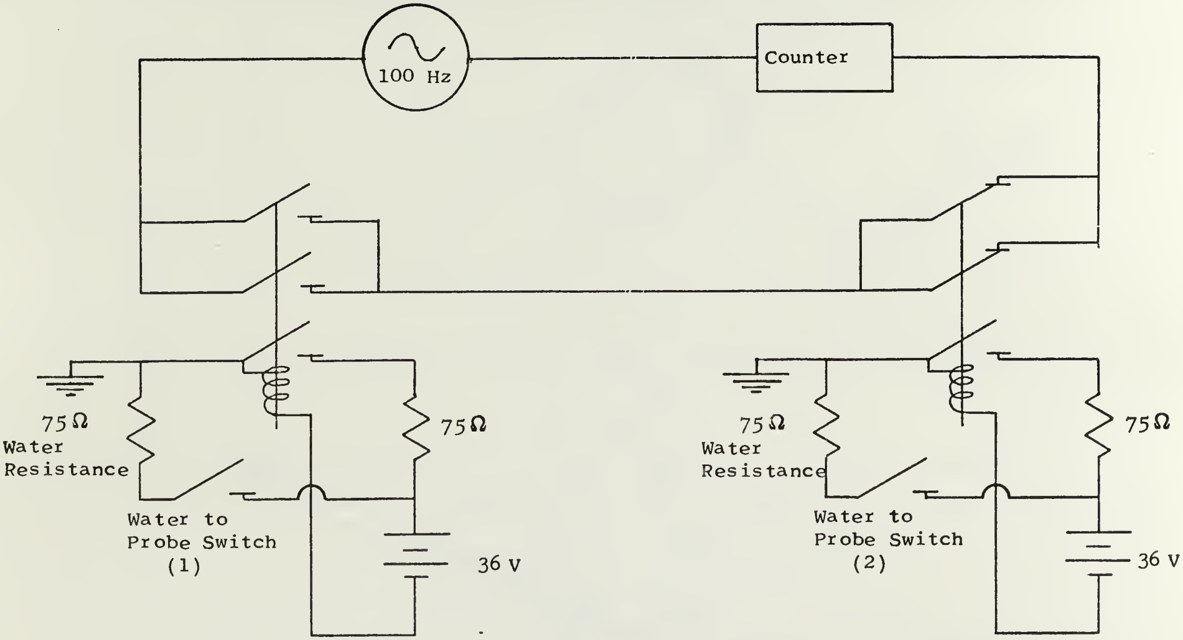
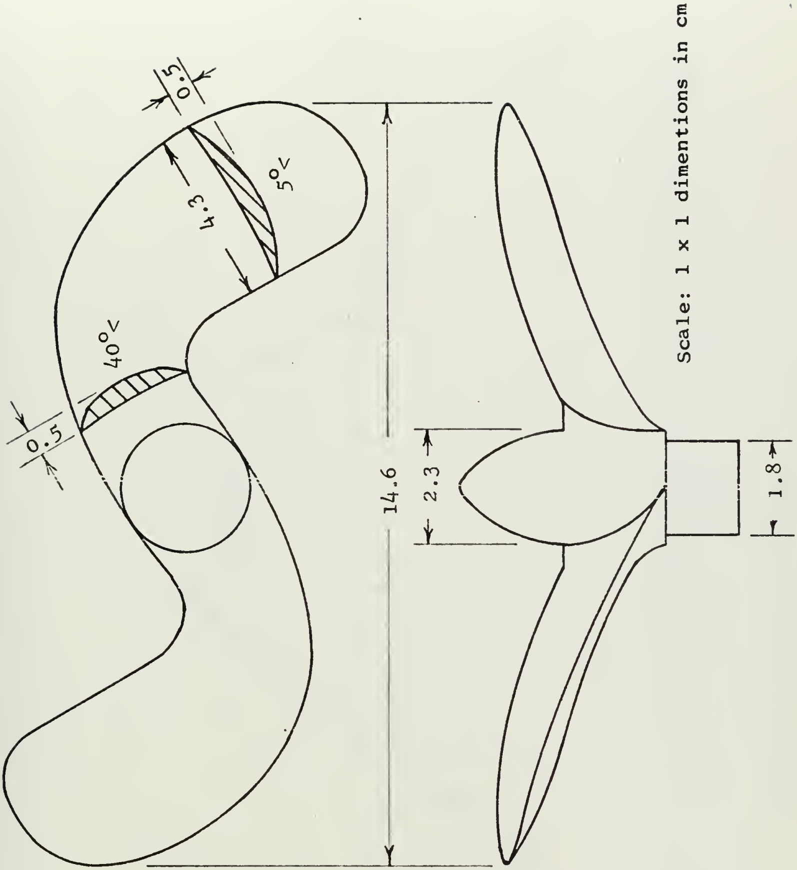


Figure 7. Water Velocity Measurement Switching Circuit



Scale: 1 x 1 dimentions in cm

Figure 8. Propeller Design

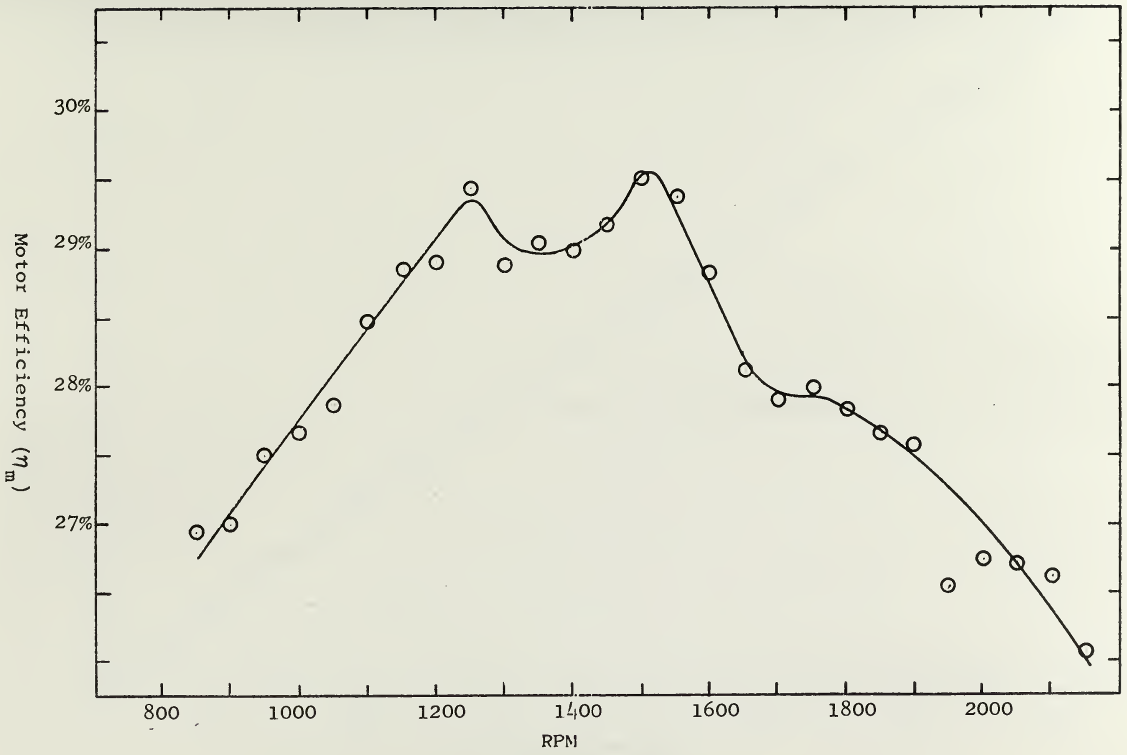


Figure 9. Motor Efficiency

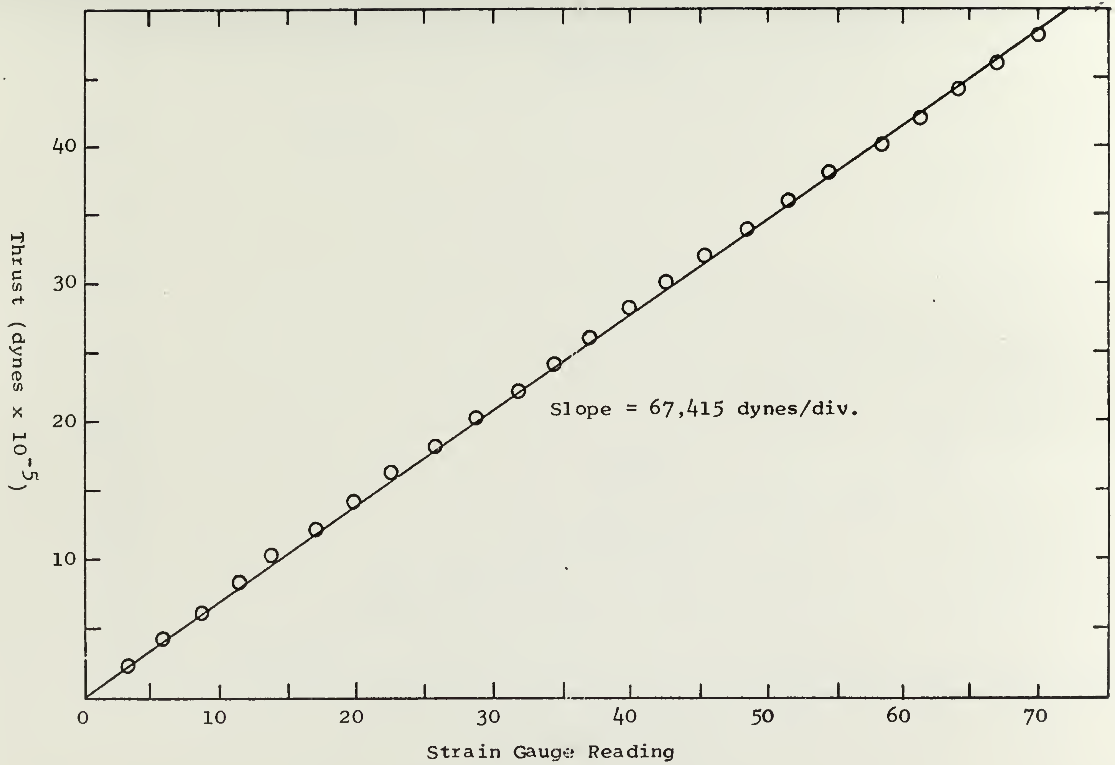


Figure 10. Strain Gauge Calibration

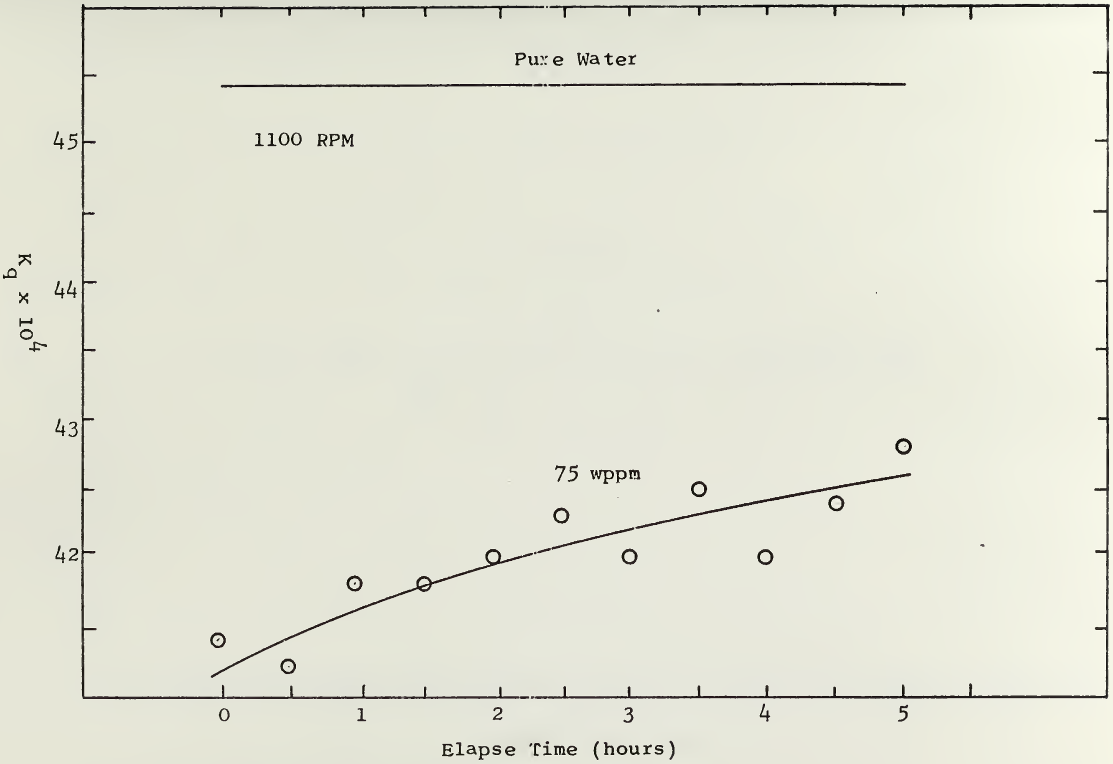


Figure 11. Torque Degradation

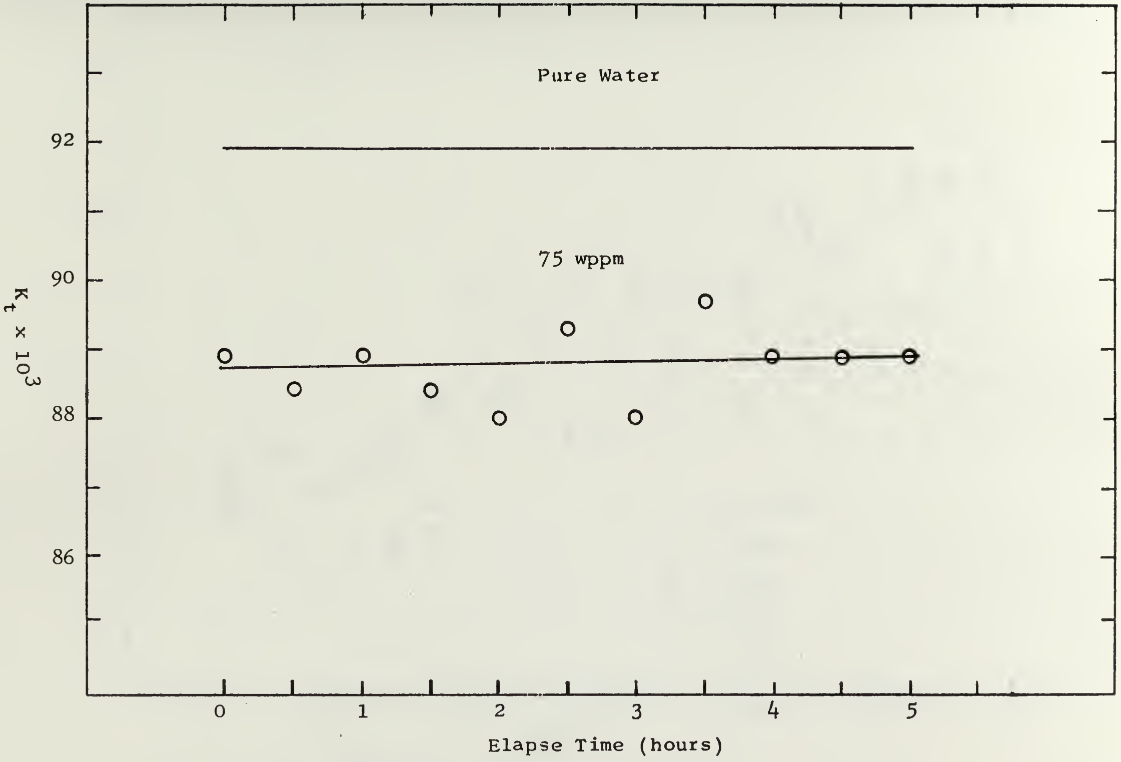


Figure 12. Thrust Degradation

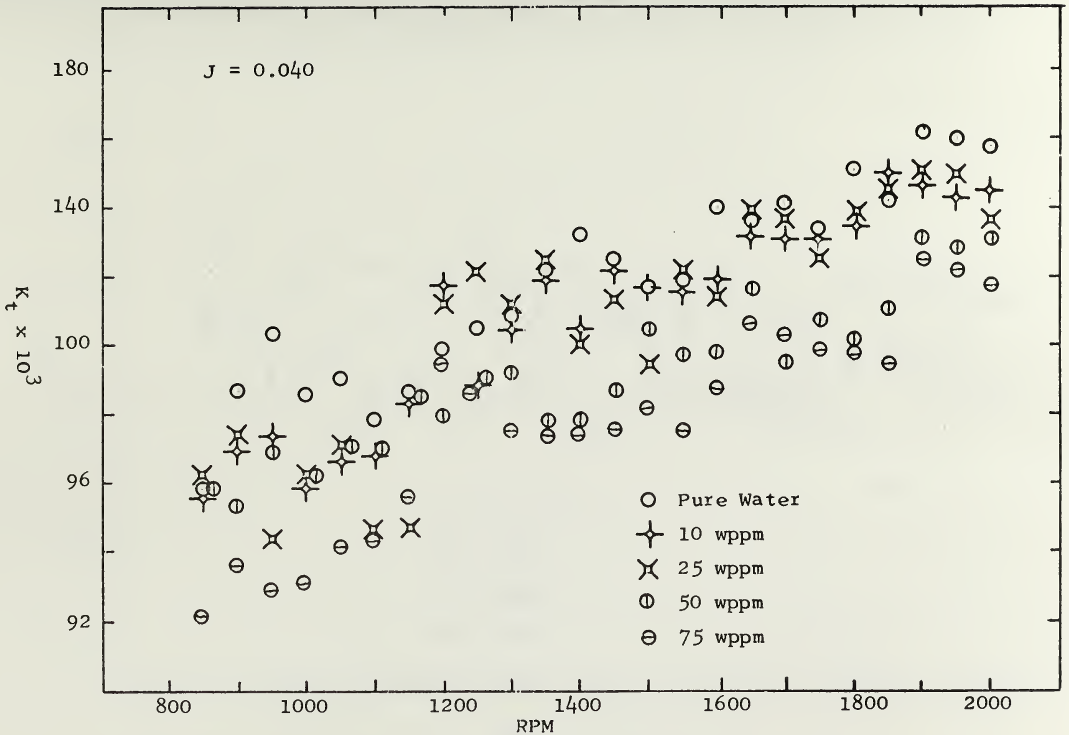


Figure 13. Thrust for J = 0.040

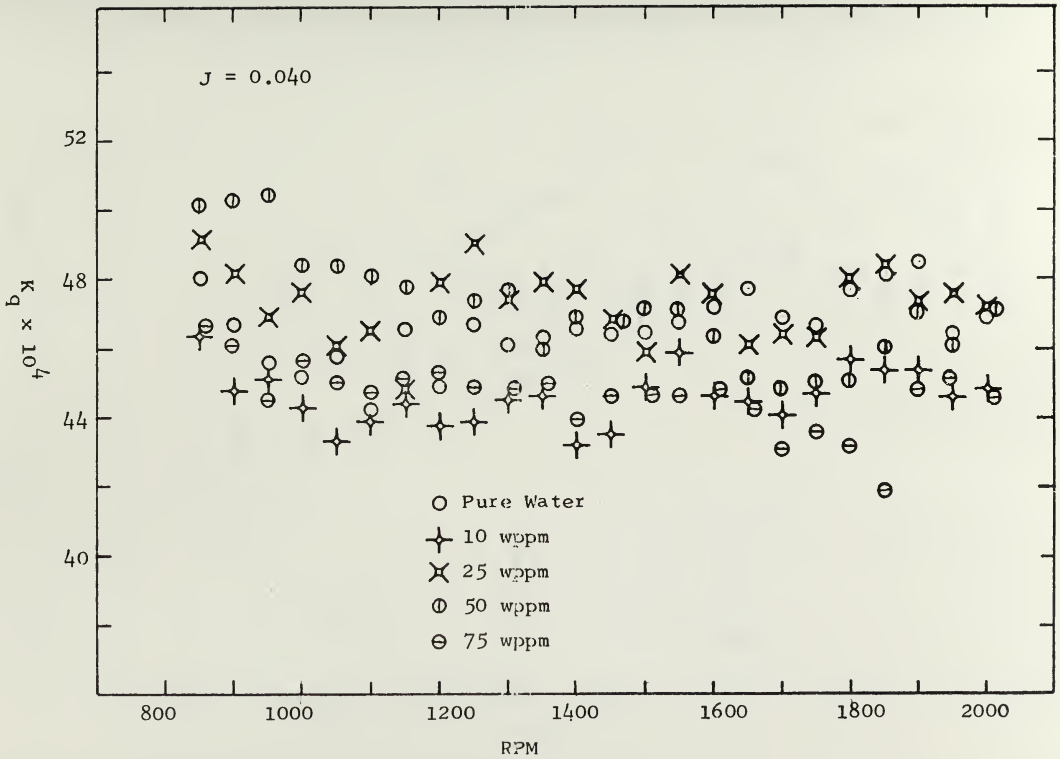


Figure 14. Torque for J = 0.040

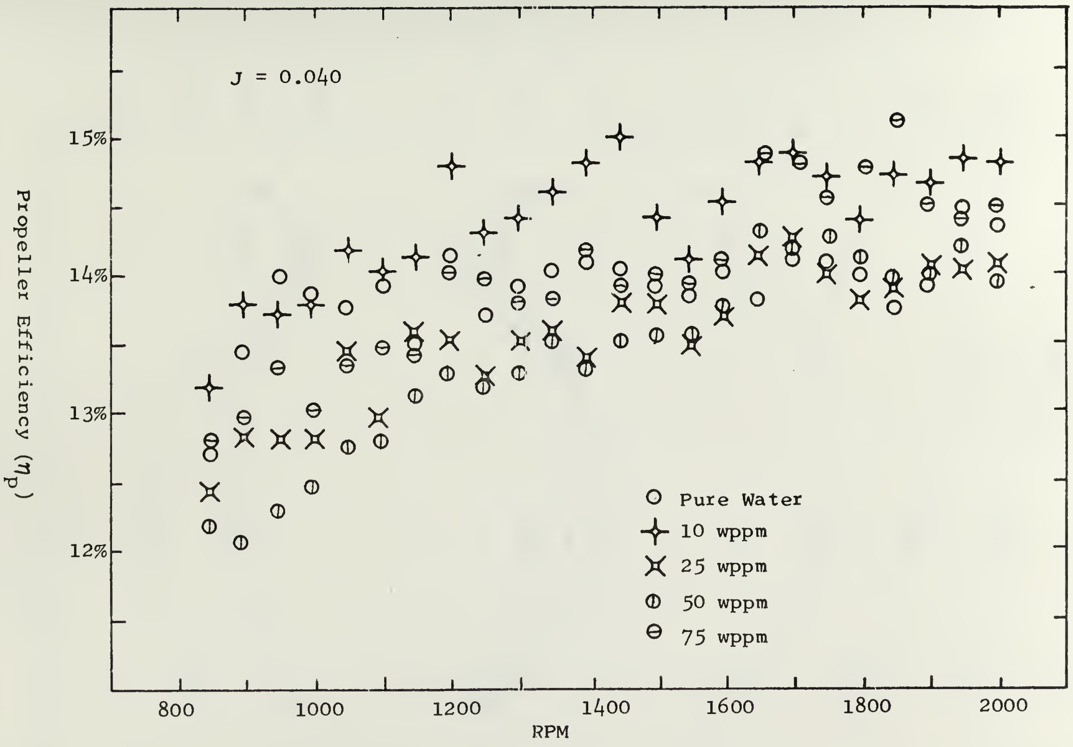


Figure 15. Propeller Efficiency for J = 0.040

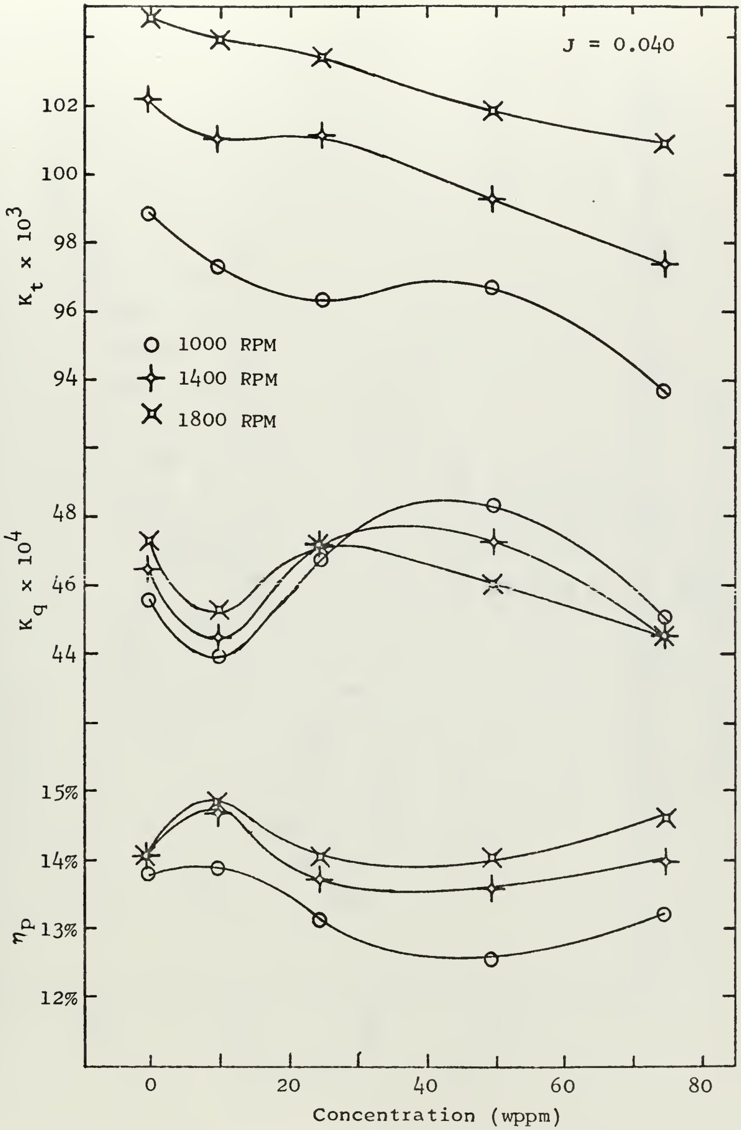


Figure 16. Propeller Performance at Constant RPM for J = 0.040

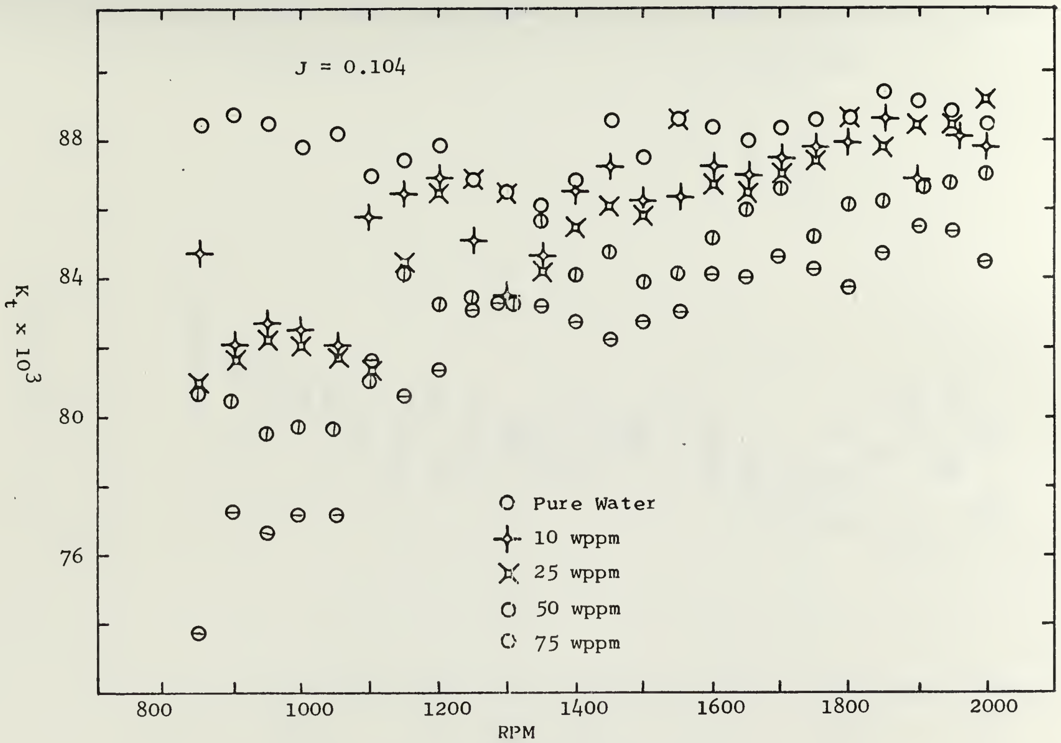


Figure 17. Thrust for J = 0.104

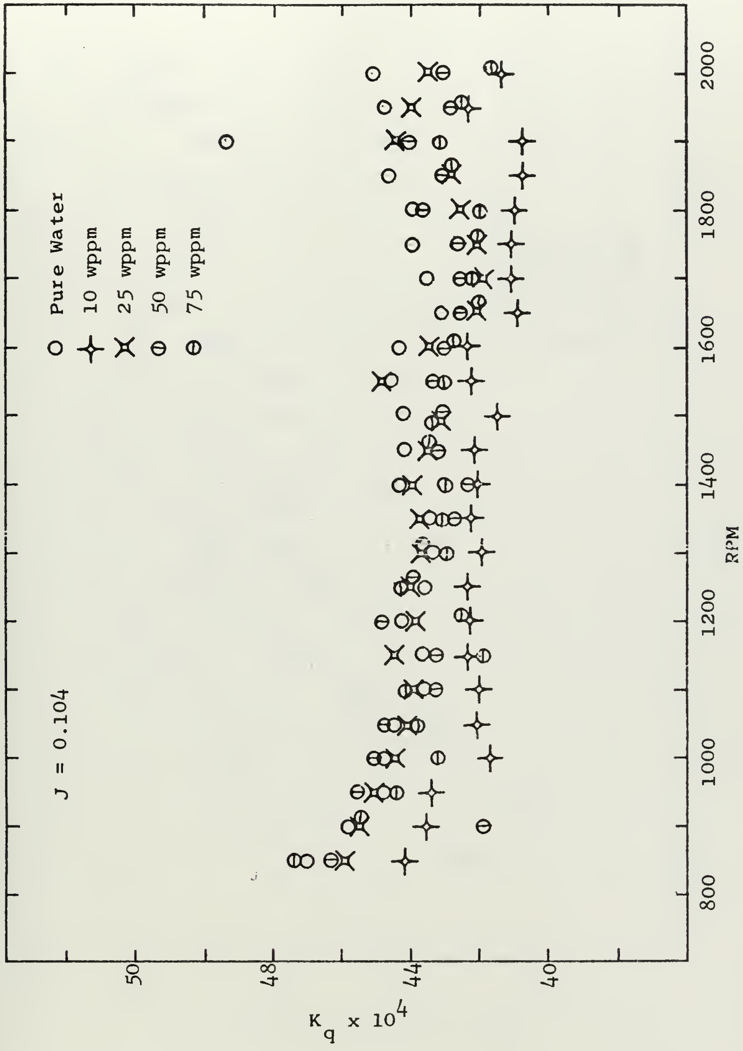


Figure 18. Torque for J = 0.104

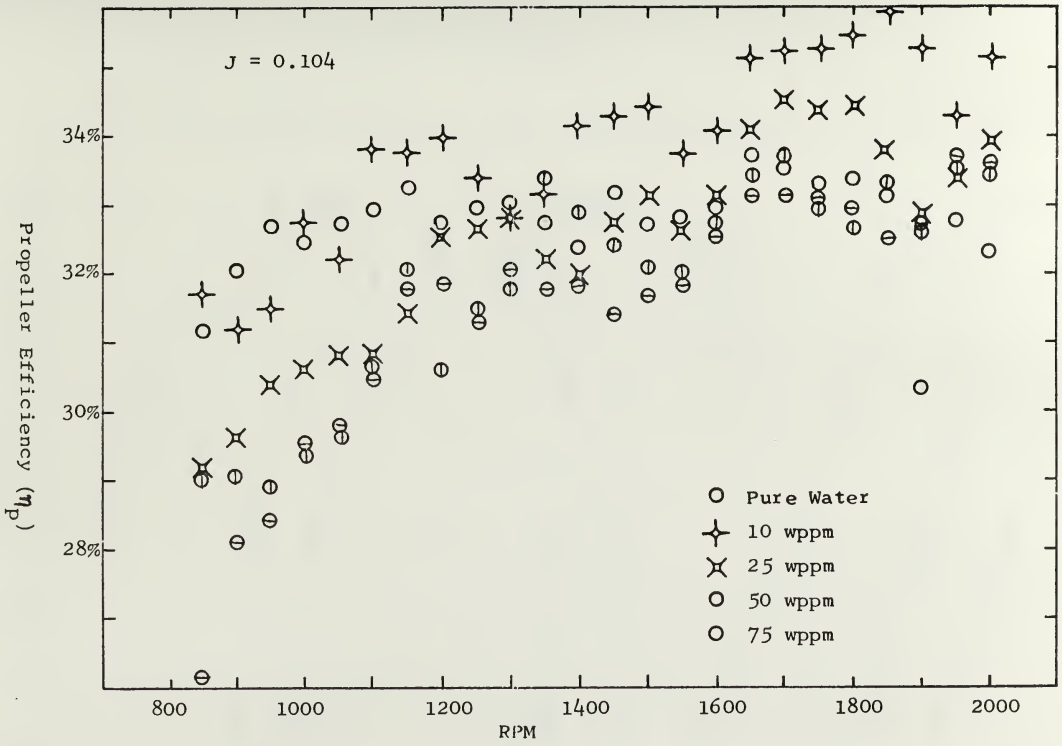


Figure 18. Propeller Efficiency for J = 0.104

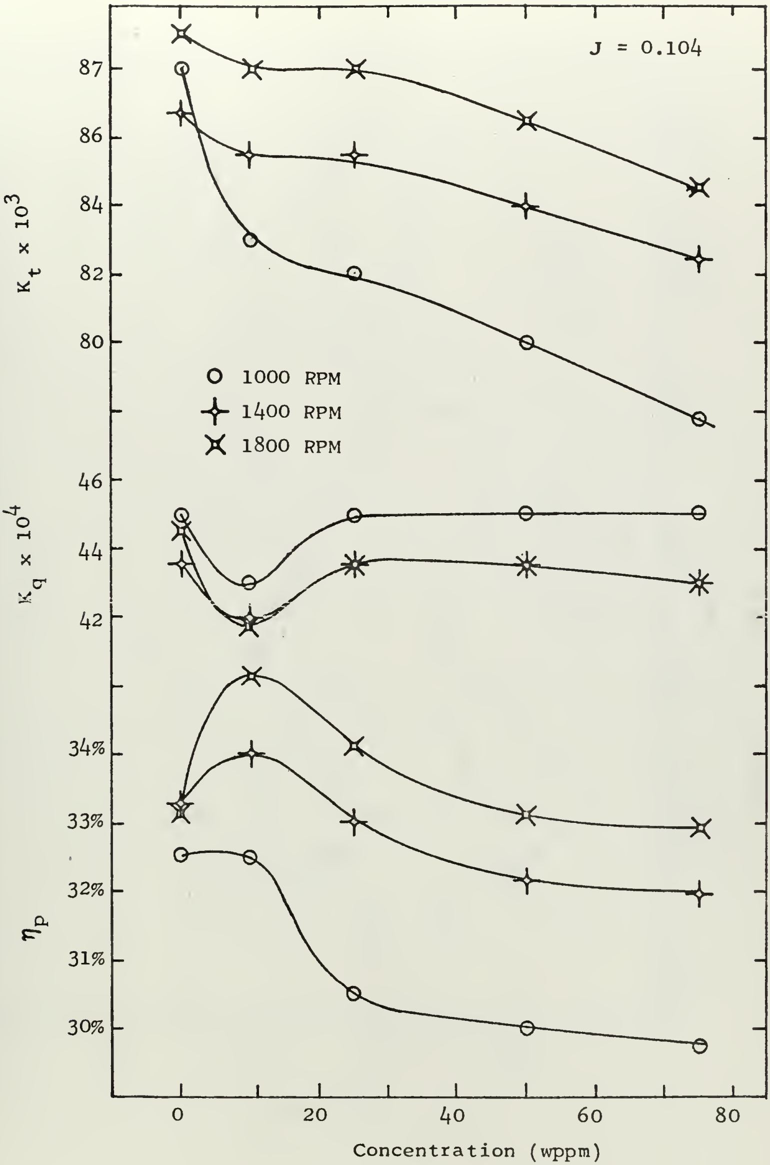


Figure 20. Propeller Performance at Constant RPM for J=0.104

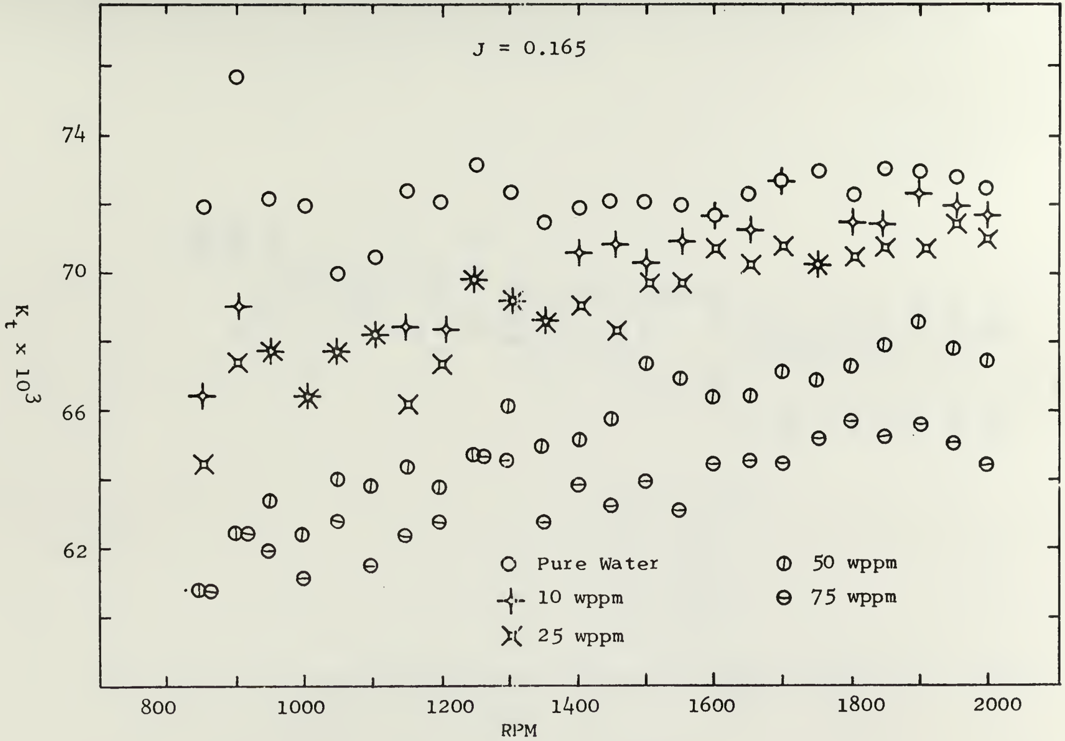


Figure 21. Thrust for J = 0.165

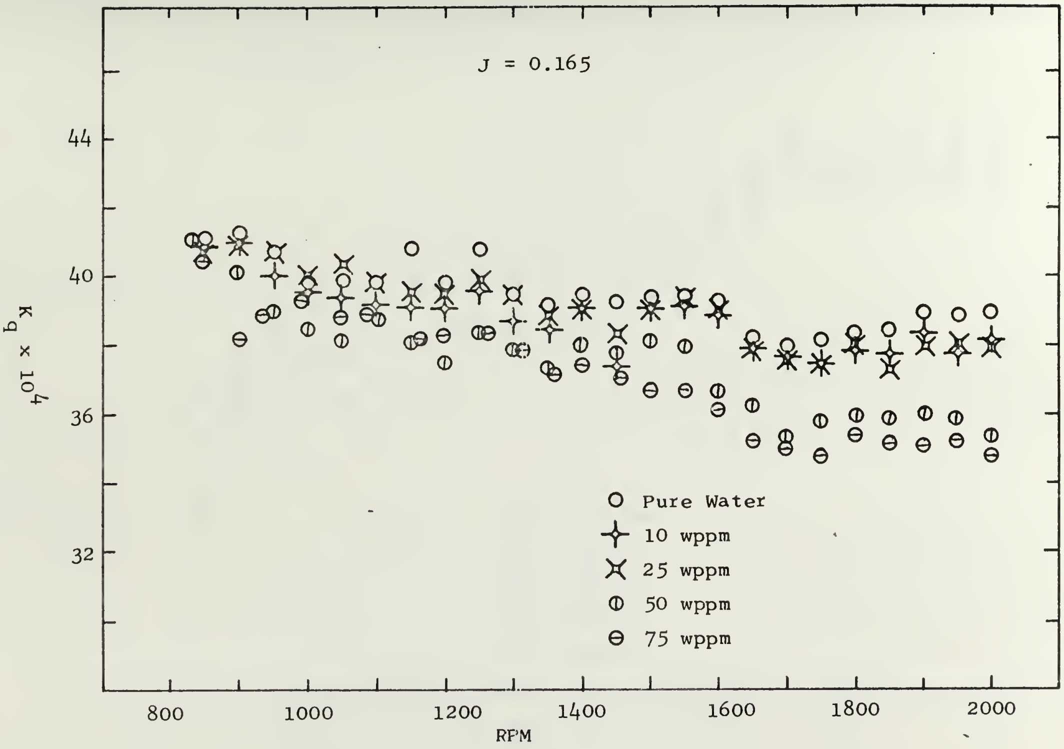


Figure 22. Torque for J = 0.165

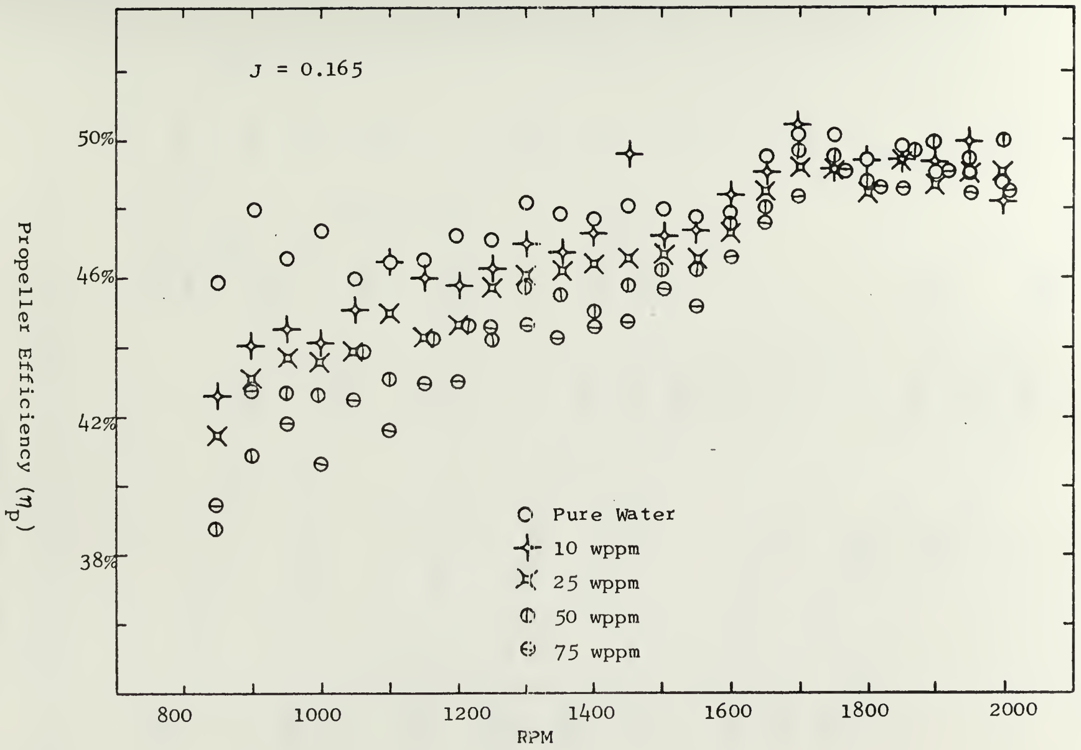


Figure 23. Propeller Efficiency for J = 0.165

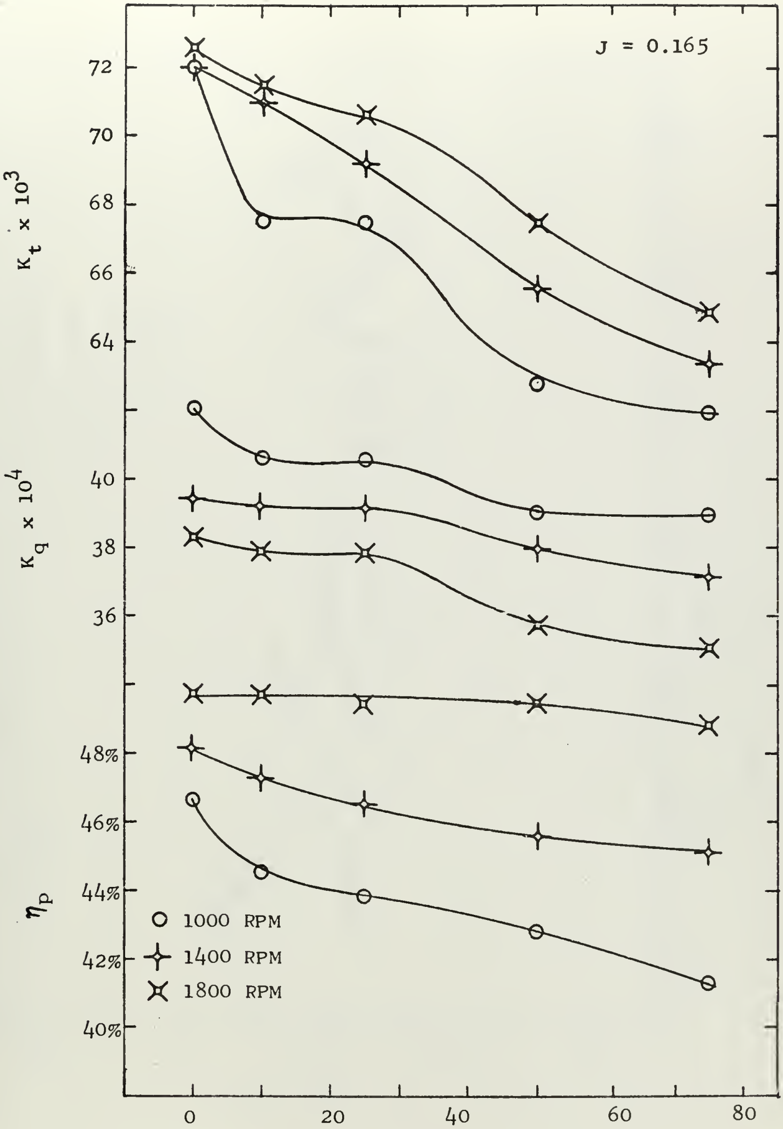


Figure 24. Propeller Performance at Constant RPM for J=0.165

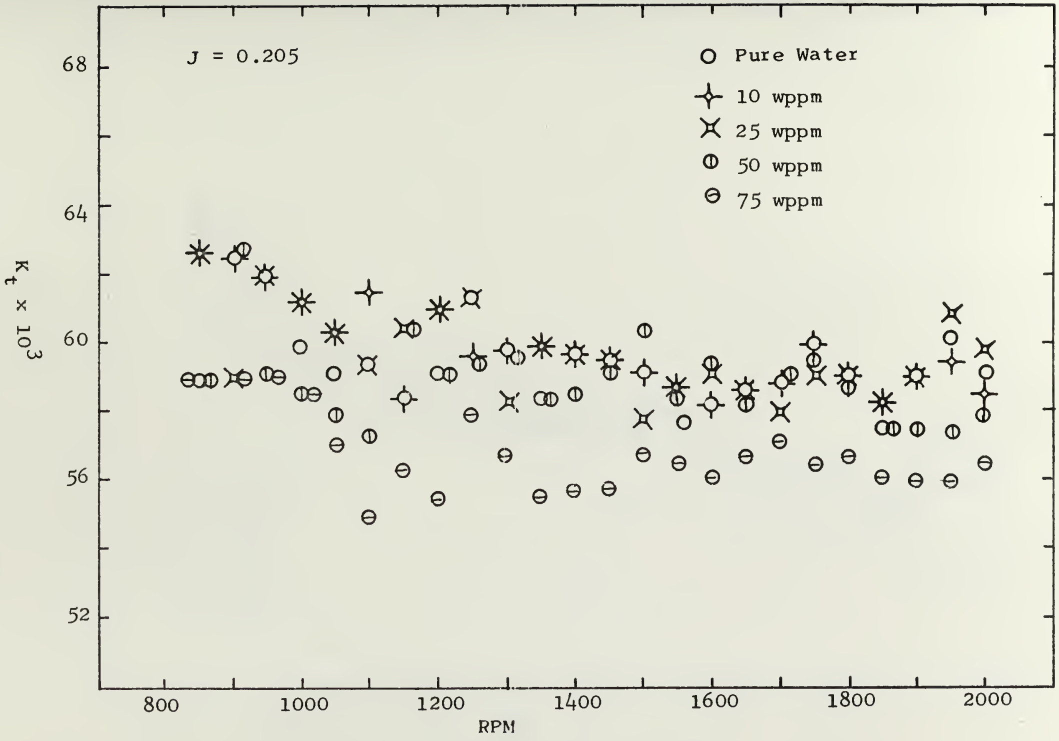


Figure 25. Thrust for J = 0.205

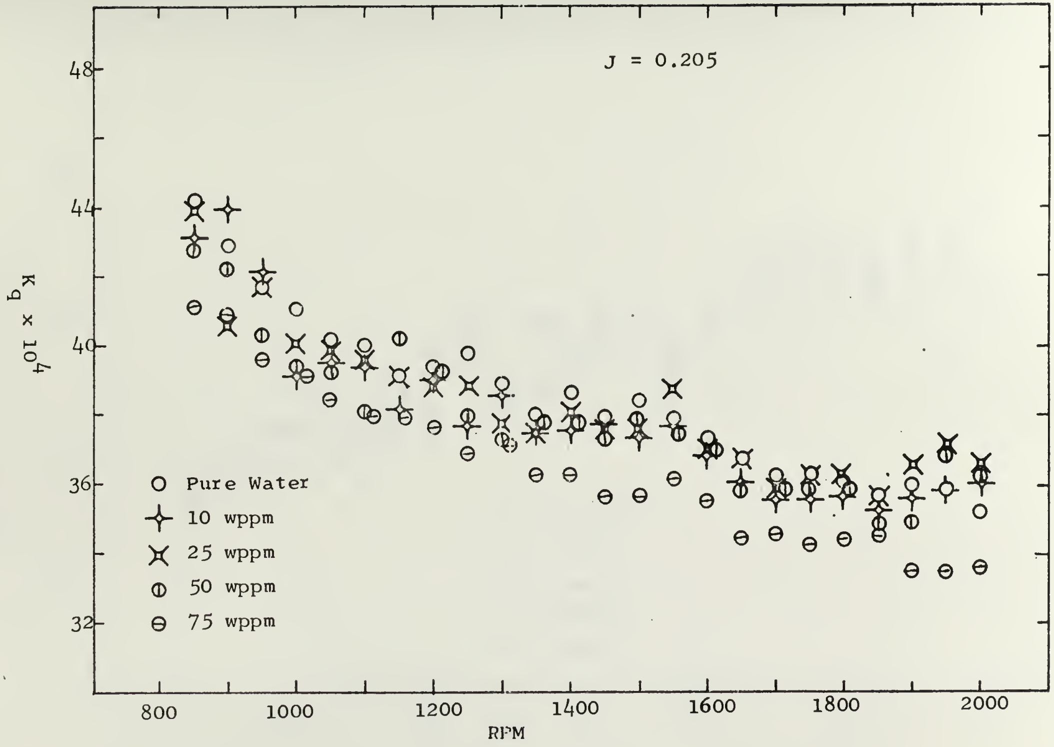


Figure 26. Torque for J = 0.205

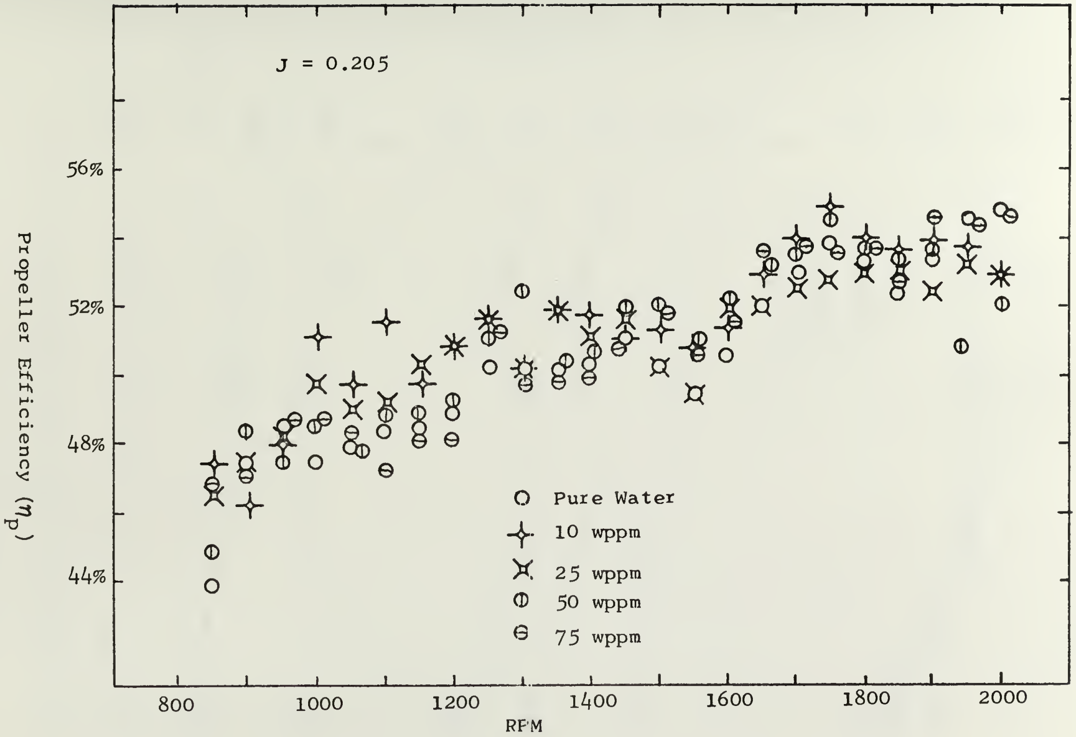


Figure 27. Propeller Efficiency for J = 0.205

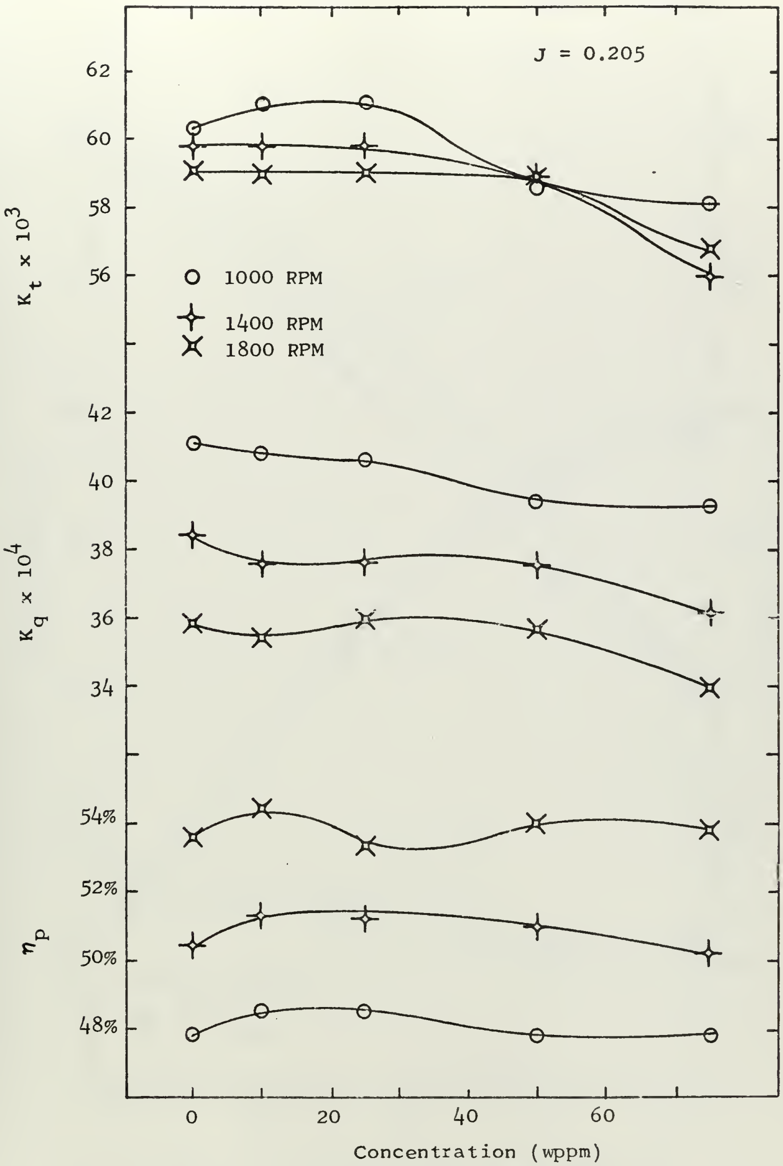


Figure 28. Propeller Performance at Constant RPM for J=0.205

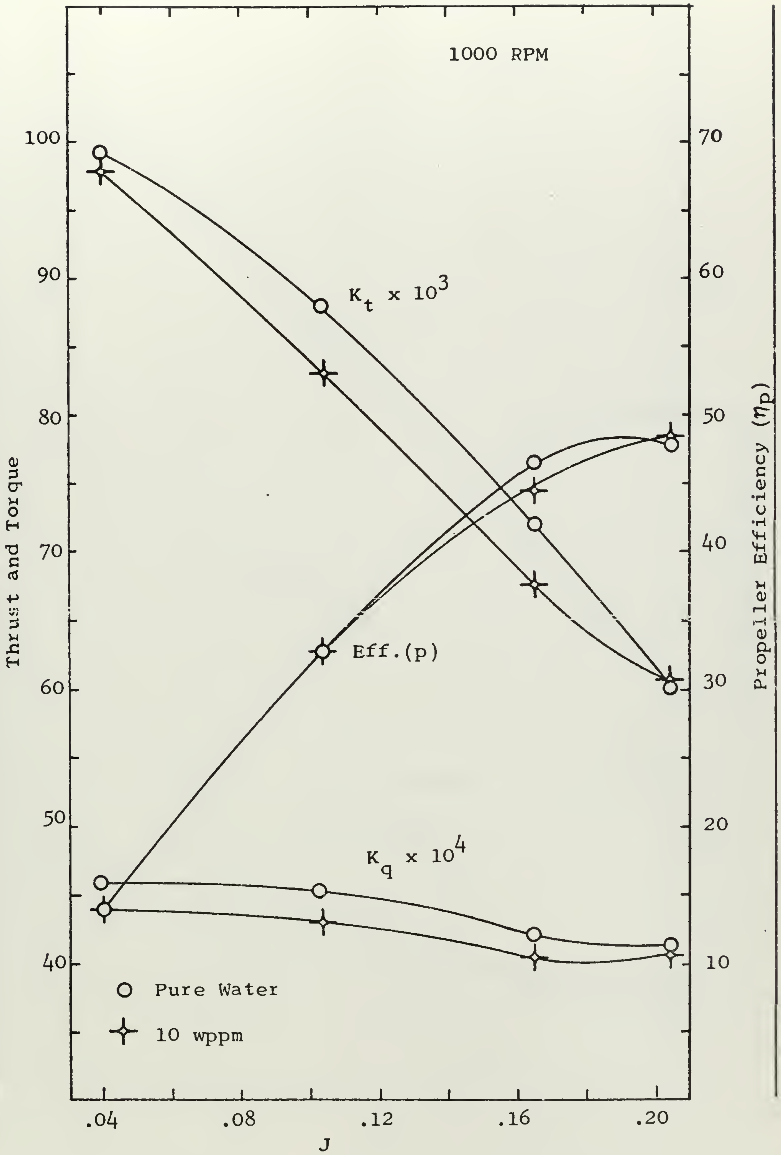


Figure 29. Propeller Performance Comparison for Optimum 10 wppm at 1000 RPM

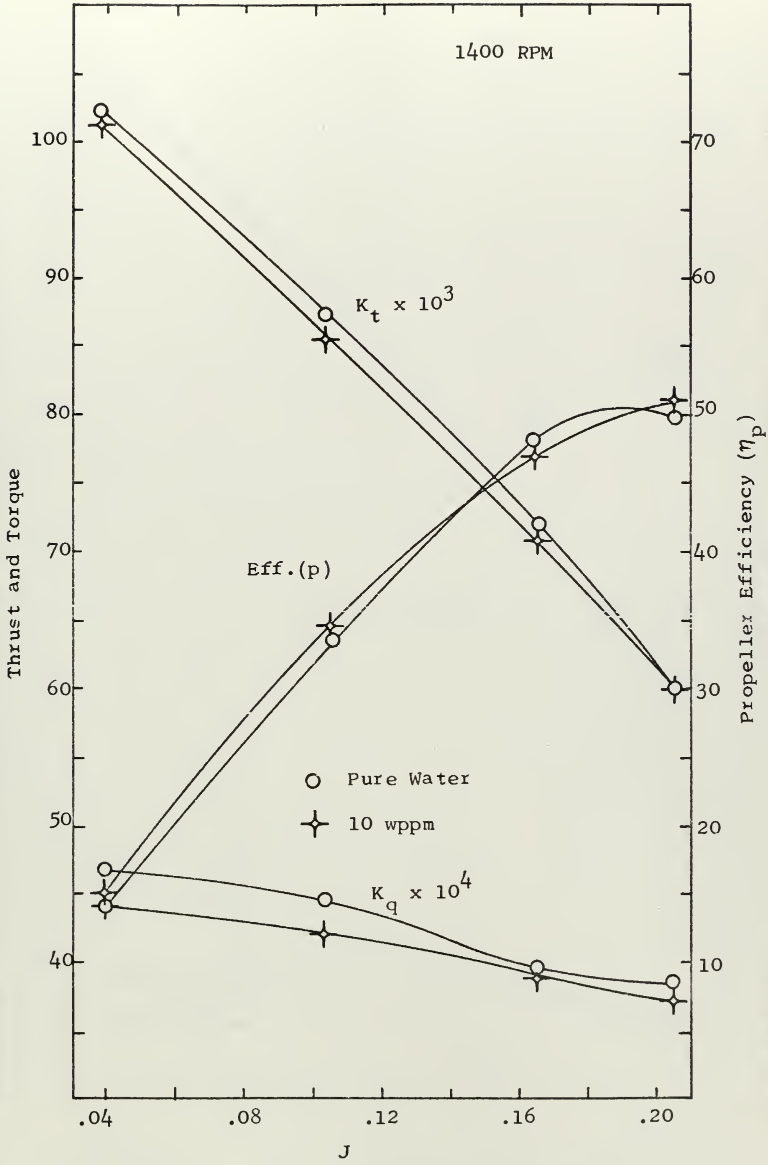


Figure 30. Propeller Performance Comparison for Optimum 10 wppm at 1400 RPM

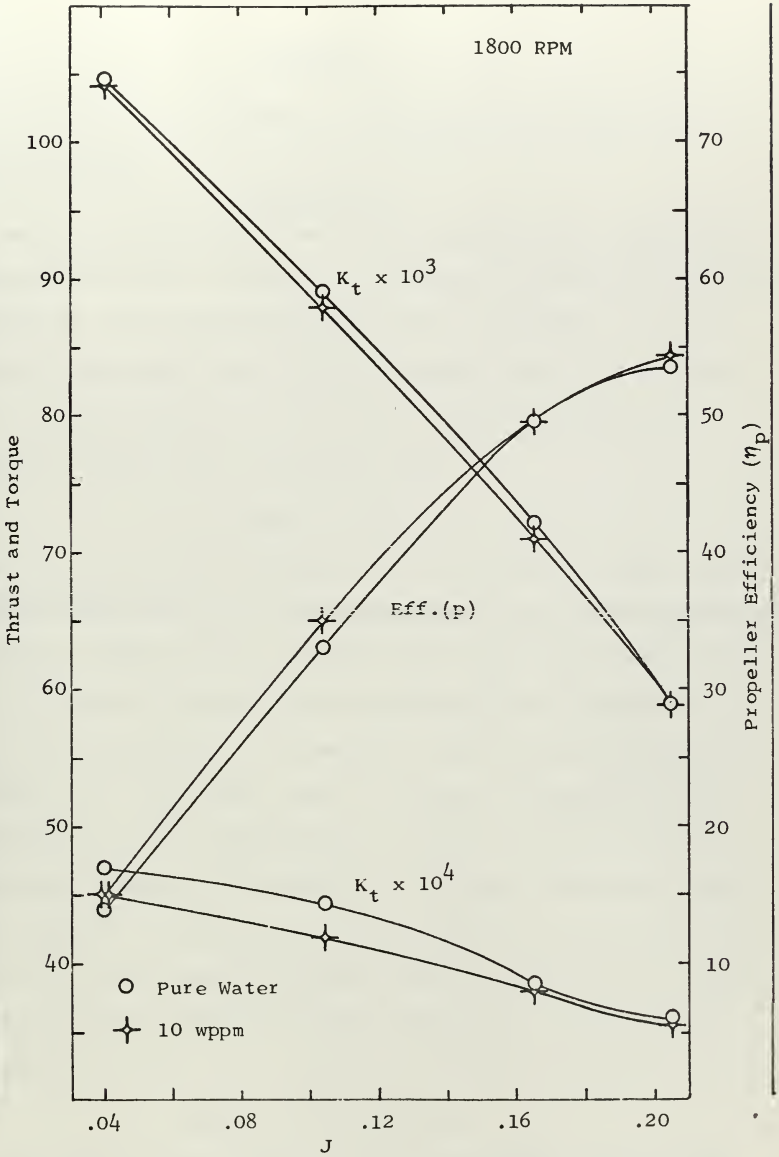


Figure 31. Propeller Performance Comparison for Optimum 10 wppm at 1800 RPM

APPENDIX A

EFFECTS OF POLYMER SOLUTIONS ON THE DISCRETE COMPONENTS OF PROPELLER NOISE

Introduction

Before this experiment was begun the possibility that polymer solutions may have an effect on the discrete component of the noise radiated by the propeller was recognized. Therefore, as an additional experiment, the radiated noise was analysed. The dominant discrete frequency radiated by a rotating propeller is a sinusoidal signal with a frequency equal to

$$f = h(\text{RPM})/60 \text{ Hertz}$$

where h is the number of blades. This is called the blade signal. The two-bladed propeller of this experiment was run in the RPM range from 850 to 2000 yielding an approximate range from 30 to 60 Hertz.

It should be realized that at these very low frequencies the tank was not expected to be anechoic, and nothing was attempted to make it so. The lowest mode of the tank was expected to be associated with the circumferential length and the cut-off frequency for this mode was estimated to be about 140 Hertz. Therefore, propeller frequencies were well below cut-off for the lowest mode of the tank, and the transfer function of the tank is expected to be a smoothly varying function of frequency in the range of interest.

Apparatus and Procedure

An Atlantic Research Model #LC-32 hydrophone, with an open-circuit sensitivity of -103 dB was placed in the center of the tank

at an arc distance of one-half meter behind the propeller. The received signal was amplified by an Atlantic Research Model #LG-1344 40dB amplifier. This combination possessed a 15 Hertz low frequency roll-off. Frequency analysis was accomplished with a Hewlett Packard Model #302A wave analyzer with a built-in 6-Hertz band pass filter. The signal to noise ratio was on the order of 20 to 1, so there was no problem using the automatic frequency control (AFC) feature of the wave analyzer.

Results and Conclusions

Figure 32 and 33 show plots of the measured signal in dB versus RPM for the various advanced coefficients. It is evident that concentrations of 10 and 75 wppm have no measureable effect on the acoustic blade signal. Data were also taken for concentrations of 25 and 50 wppm with the same results.

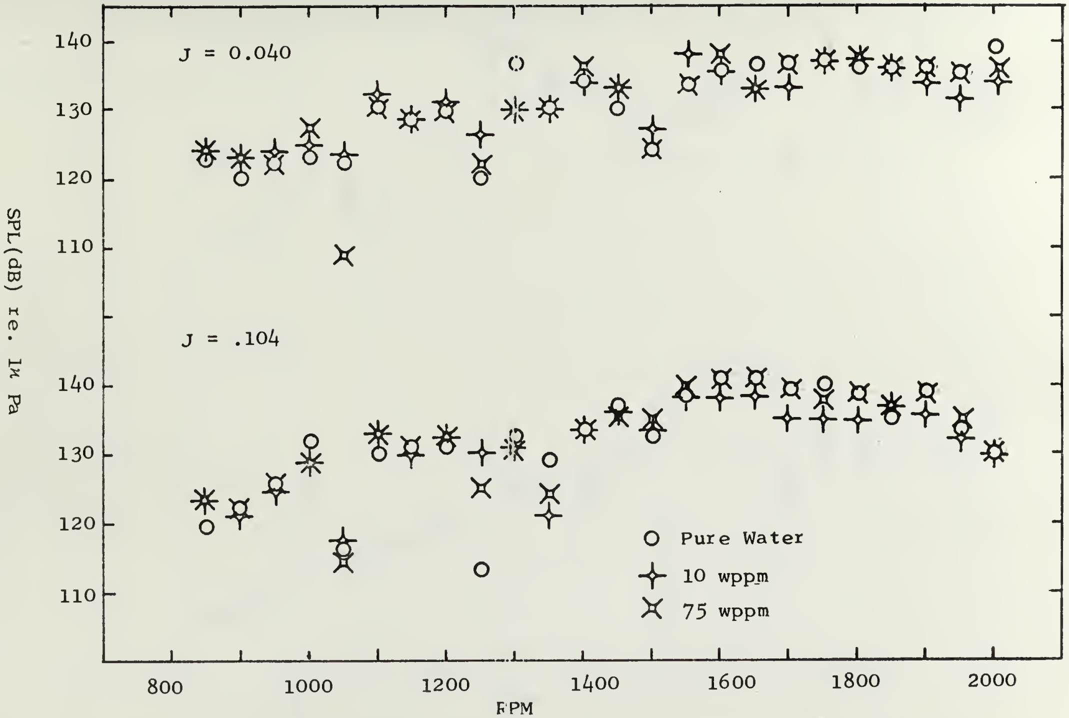


Figure 32. Acoustic Blade Signal for J = 0.040, 0.104

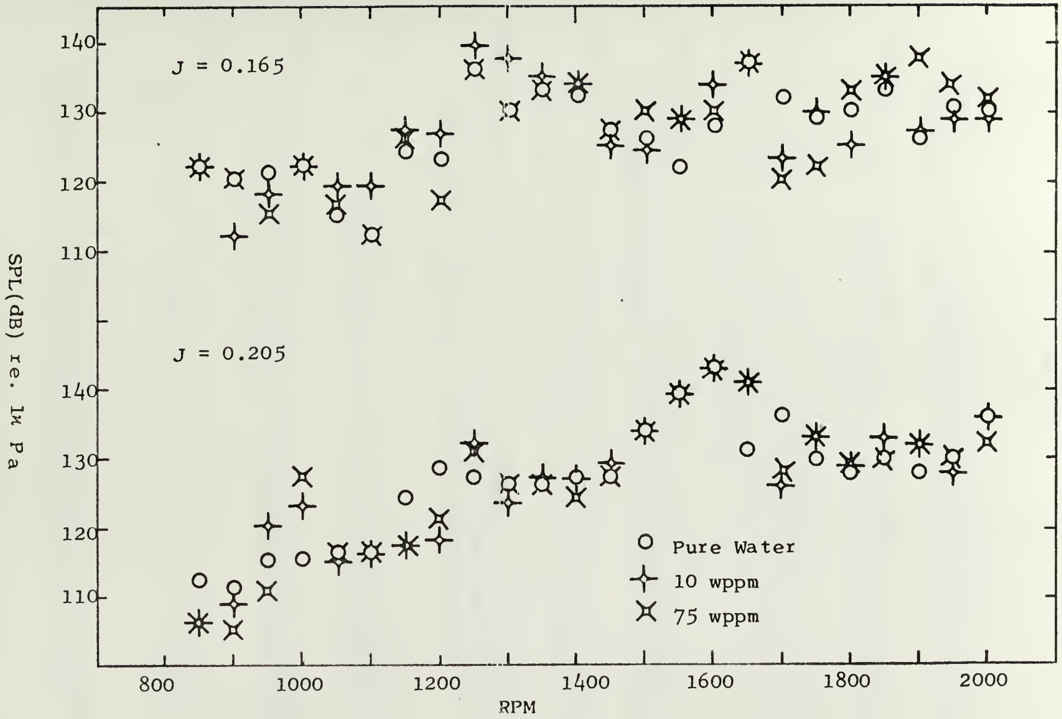


Figure 33. Acoustic Blade Signal for J = 0.165, 0.205

BIBLIOGRAPHY

1. Bilegen, E.A., "On the Stability of Viscoelastic Flow Due to a Rotating Disk," American Institute of Chemical Engineers Symposium on Drag Reduction: No. III, V. 67, p. 74-84, 1971.

2. Dodge, D.W., and Metzner, A.B., "Turbulent Flow of Non-Newtonian Systems," American Institute of Chemical Engineers Journal, V. 5, p. 189-204, June 1959.

3. Goldstein, R.J., Adrian, R.J., and Kreid, D.K., Turbulent and Transition Pipe Flow of Dilute Aqueous Polymer Solutions," Industrial and Engineering Chemistry Fundamentals, V. 8, No. 3, p. 498-502, August 1969.

4. Goldstein, S., "On the Resistance to the Rotation of a Disk Immersed in a Fluid," Proceedings of the Cambridge Philosophical Society, V. 31, p. 232-241, April 1935.

5. Granville, P.S., "The Frictional Resistance and Boundary Layer of Flat Plates in Non-Newtonian Fluids," Journal of Ship Research, V. 6, p. 43, 1962.

6. Hershey, H.C., and Zakin, J.L., "Existence of Two Types of Drag Reduction in Pipe Flow of Dilute Polymer Solutions, "Industrial Engineering Chemistry Fundamentals, V. 6, p. 381-387, August 1967.

7. Hoyt, J.W. and Fabula, A.G., "The Effects of Additives on Fluid Friction," Fifth Symposium on Naval Hydrodynamics, p. 997, Bergen, Norway, 1964.

8. Hydronautics, Incorporated Technical Report 353-5, Pressure Fluctuation Measurements in Dilute Polymer Solutions, by D.N. Contractor, September 1967.

9. Hydronautics, Incorporated Technical Report 909-1 Final, Development and Model Tests of a Surface Ship Additive System, by A. Gollan, M.P. Tulin, and S.L. Rudy, November 1970.

10. Hydronautics, Incorporated Technical Report 7101-1, Some Techniques of Ejecting Additive Solutions for Drag Reduction, by J. Wu, February 1971.

11. Kinnier, J.W., A Correlation Between Friction Production and Molecular Size for the Flow of Dilute Aqueous Polyethylene-Oxide Solutions in Pipes, Ph.D. Thesis, United States Naval Postgraduate School, Monterey, California, June 1970.

12. Kowalski, T., "Reduction of Frictional Drag by Non-Newtonian Additives," Naval Engineers Journal, V. 78, p. 293, 1966.

13. Kowalski, T., "Effect of Polymer Additives on Propeller Performance," Journal of Hydronautics, V. 5, No. 1, p. 11-14, January 1971.

14. McNally, W.A., Heat and Momentum Transport in Dilute Polyethylene-Oxide Solutions, Ph.D. Thesis, University of Rhode Island, 1968.

15. Merrill, E.W., Mickley, H.S., and Ram, A., "Degradation of Polymers in Solution Induced by Turbulence and Droplet Formation," Journal of Polymer Science, V. 62, p. S109-S113, 1962.

16. Metzner, A.B., and Park, M.G., "Turbulent Flow Characteristics of Viscoelastic Fluids, Journal of Fluid Mechanics, V. 20, p. 291, 1964.

17. Miloh, T., Boundary Layer on a Disk Rotating in Dilute Polymer Solutions, MSc Thesis, Technion, Israel Institute of Technology, 1969.

18. Miloh, T., and Poreh, M., "The Resistance to Rotation of Free and Enclosed Disks," Journal of Applied Mechanics, Trans of the ASME, (Pre-print-Paper No. 71-APM-25, 1971).

19. Mysels, K.J., Flow of Thickened Fluids, U.S. Patent 2, 492, 173, 27 December 1949.

20. Naval Ordnance Test Station Report TP 3385. NAVWEPS Report 8434, Drag Reduction Through the Use of Additive Fluids, by A.G. Fabula and Others, March 1964.

21. Naval Ordnance Test Station. NOTS-TP-4284, Applications of Polymer Solutions to Torpedo Drag Reduction, by R.K. Coltpredson, April 1967.

22. Naval Ordnance Test Station Report TP 3713. NAVWEPS Report 8666, Studies of Drag Reduction by Fluid Ejection with a Self-propelled Torpedo, by J.H. Green and Others, April 1965.

23. Naval Undersea Research and Development Center. NUC-TP-141, A Proposed High-Speed Experiment on U.S.S. Albacore, (AGSS-569), by J.W. Hoyt and Others, May 1969.

24. Naval Undersea Research and Development Center. NUC-TP-136, Ablative Coatings in Drag Reduction Applications, by A.B. Arranaga, July 1969.

25. Naval Undersea Research and Development Center. NUC-TP-218, A Proposed Second High-Speed Experiment on U.S.S. Albacore (AGSS-569), by J.W. Hoyt, January 1971.

26. Naval Undersea Warfare Center. NUWC-TP-34, Drag-Reduction Studies with a Boat-Towed Model, by E.D. Swanson, May 1968.

27. Office of Naval Research Contract Nonr 710(63), The Effect of Dilute Solutions of Drag Reducing Polymers on Radiated Flow Noise, by J.M. Killen and S.D. Crist, July 1967.

28. Office of Naval Research Contract N0014-67-A-0298-002, Turbulent Flow Drag Reduction and Degradation with Dilute Polymer Solutions, by R.W. Paterson, June 1969.

29. Pruitt, G.T., and Cranford, H.R., Effect of Molecular Weight and Segmental Constitution on the Drag Reduction of Water Soluble Polymers, David Taylor Model Basin Report No. 1, The Western Company, Research Division, Dallas, Texas, April 1965.

30. Ram, A., and Tamir, A., "Structural Turbulence in Polymer Solutions," Journal of Applied Polymers Science, V. 8, p. 2751-2762, 1969.

31. Saunders, H.E., Hydrodynamics in Ship Design, V. 1, p. 248-255, 511-513, The Society of Naval Architects and Marine Engineers, 1957.

32. Saunders, H.E., Hydrodynamics in Ship Design, V. 2, p. 878, The Society of Naval Architects and Marine Engineers, 1957.

33. Savins, J.G., "Drag Reduction Characteristics of Solutions of Macromolecule in Turbulent Pipe Flow," Society of Petroleum Engineers Journal, p. 203-214, September 1964.

34. Schlichting, H., Boundary Layer Theory, 4th ed., McGraw-Hill, 1960.

35. Shaver, R.G., and Merrill, E.W., "Turbulent Flow of Psuedo-plastic Polymer Solutions in Straight Cylindrical Tubes," American Institute of Chemical Engineers Journal, V. 5, p. 181-188, June 1959.

36. United States Postgraduate School Report NPS-59SL1021A, Flow of Dilute Polymer Solutions about Circular Cylinders, by T. Sarpkaya and P.G. Rainer, 26 February 1971.

37. Toms, B.A., "Some Observations on the Flow of Linear Polymer Solutions Through Straight Pipes at Large Reynolds Numbers,". Proceedings of the First International Congress on Rheology, V. 2, p. 135, North Holland Publishing Company, Amsterdam, 1948.

38. Vanoni, V.A., "Transportation of Suspended Sediment by Water," Transactions of American Society of Civil Engineers III, 1946.

39. Virk, P.S., The Toms Phenomenon-Turbulent Pipe Flow of Dilute Polymer Solutions, Ph.D. Thesis, Massachusetts Institute of Technology, 1966.

40. Vogel, W.M. and Patterson, A.M., "An Experimental Investigation of the Effect of Additives Injected into Boundary Layer of an Underwater Body," Fifth Symposium on Naval Hydrodynamics, Bergen, Norway, September 1964.

41. Wells, C.S., Jr., and Others, "Turbulence Measurements in Pipe Flow of a Drag Reducing Non-Newtonian Fluid," American Institute of Aeronautics and Astronautics Journal, V. 6, p. 250-257, February 1968.

42. White, W.D. and McEligot, D.M., "Transition of Mixtures of Polymers in a Dilute Aqueous Solution," Journal of Basic Engineering, Trans of the ASME, (Pre-print-paper No. 69 - WA/FE26, 1969).

43. Wu, J., "Lift Reduction in Additive Solutions," Journal of Hydronautics, V. 3, No. 4, p. 198-200, October 1969.

INITIAL DISTRIBUTION LIST

No. Copies

1. Defense Documentation Center 2
Cameron Station
Alexandria, Virginia 22314

2. Library, Code 0212 2
Naval Postgraduate School
Monterey, California 93940

3. Prof. J.V. Sanders 5
Department of Physics Code 61Sd
Naval Postgraduate School
Monterey, California 93940

4. LCDR L.H. Henderson 5
1624 Macon
Aurora, Colorado 80010

5. Dr. J.W. Hoyt 1
Naval Undersea Research & Development Center
3202 E. Foothill Blvd.
Pasadena, California 91107

6. Dr. A.G. Fabula 1
Code 6005, Bldg 106
Naval Undersea Research & Development Center
San Diego, California 92132

7. Mr. D. Beardsley 3
Shakespeare Products Division
Kalamazoo, Michigan 49001

8. CAPT G.L. Page 1
PERS B-10
Bureau of Naval Personnel, Arlington Annex
Washington, D.C. 20370

9. CDR L. Phillips 1
Staff, Commander Naval Air Forces, US Pacific Fleet
NAS North Island
San Diego, California 92135

10. LCDR Robin J. White 1
SMC #1438
Naval Postgraduate School
Monterey, California 93940

11.	Prof. T.M. Houlihan Code 59Hm Naval Postgraduate School Monterey, California 93940	1
12.	Office of Naval Research Code 480D Arlington, Virginia 22217	1

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Postgraduate School Monterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP

3. REPORT TITLE

Effects of Polyethylene-Oxide Solutions on the Performance of a Small Propeller

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Master's Thesis; September 1971

5. AUTHOR(S) (First name, middle initial, last name)

Lee H. Henderson

6. REPORT DATE September 1971	7a. TOTAL NO. OF PAGES 69	7b. NO. OF REFS 43
8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)	
b. PROJECT NO.		
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.		

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Postgraduate School Monterey, California 93940

13. ABSTRACT

The thrust and torque were measured and the efficiency calculated for a 14.6-cm diameter, two-bladed propeller in aqueous solutions of polyethylene oxide, WSR-301, with concentrations ranging from 0 to 75 wppm (weight parts per million). The full operating range of the propeller was studied. For the propeller operating under heavily loaded conditions, the thrust decreases with increasing concentration while the torque passed through a minimum at 10 wppm. This resulted in a increase in efficiency (η_p=VT/Qw, where V is the speed of advance, T is the thrust, Q is the torque, and w is the angular frequency of rotation) of up to 10% at 10 wppm. For the propeller operating under lightly loaded conditions, the polymer had little effect on performance. If these results are applicable to full-sized propellers, drag-reducing polymers would not effect propeller performance significantly. Acoustic measurements were also made and they indicate that the polymer has no effect on the strength of the discrete components of the radiated propeller noise.

4 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Propeller Performance						
Polyethylene-Oxide						
Polymeric Friction Reduction						
Acoustic Blade Signal						
Propeller						
Polymer						
Hydrofoil						

130744
Thesis
H4395 Henderson
c.1 Effects of polyethylene-oxide solutions on the performance of a small propeller.
BINDERY
3 [illegible] 33528
3 AUG 88 33528

Thesis 130744
H4395 Henderson
c.1 Effects of polyethylene-oxide solutions on the performance of a small propeller.

thesH4395
Effects of polyethylene-oxide solutions
3 2768 001 91838 6
DUDLEY KNOX LIBRARY